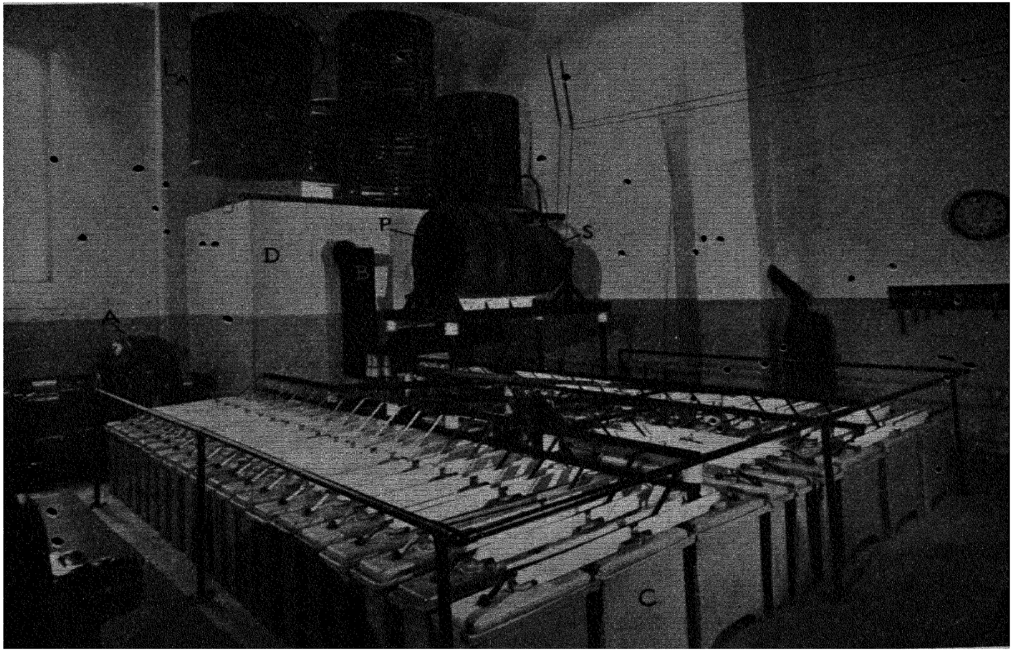
UNIVERSAL
LIBRARY

OU_174035

UNIVERSAL
LIBRARY

WIRELESS TELEGRAPHY AND TELEPHONY

FIRST PRINCIPLES, PRESENT PRACTICE AND TESTING



A Marconi 60-kw. Spark Transmitting Set.

WIRELESS TELEGRAPHY AND TELEPHONY

FIRST PRINCIPLES, PRESENT PRACTICE AND TESTING

BY

H. M. DOWSETT

MEMBER OF THE INSTITUTION OF ELECTRICAL ENGINEERS
FELLOW OF THE PHYSICAL SOCIETY OF LONDON
MEMBER OF THE INSTITUTE OF RADIO ENGINEERS

ALL RIGHTS RESERVED

LONDON
THE WIRELESS PRESS, LTD.
12 & 13 HENRIETTA STREET, STRAND, W.C.2
NEW YORK, WIRELESS PRESS INC., 233 BROADWAY
1920

THE WIRELESS PRESS, LTD.

FOREIGN AND COLONIAL AGENCIES

SYDNEY, N.S.W.: 97 CLARENCE STREET
MELBOURNE: 422/4 LITTLE COLLINS STREET
MADRID: LA PRENSA RADIOTELEGRAFICA, 43 CALLE DE ALCALA
ROME: AGENZIA RADIOTELEGRAFICA ITALIANA, VIA GREGORIANA 36
AMSTERDAM: NEDERLANDSCH PRESBUREAU RADIO, WETERINGSCHANS 104

PREFACE

WIRELESS Telegraphy at its inception was the commercial application of quite a small group of physical phenomena, but in its rapid growth it has been fostered by discoveries in every branch of physics and by the genius of many inventors.

Its application to-day makes use of the most delicate instruments on the one hand, and very special heavy electrical machinery on the other, and its study embraces a diversity of subjects.

The object of this small volume is not an all-embracing one. It is designed to act as a connecting link between the elementary text-book and the advanced treatise or the specialised text-book, and in particular to meet the demand for a book of instruction which can be used in sequence to *The Handbook of Technical Instruction for Wireless Telegraphists* by J. C. Hawkhead and the present author.

In order to assist the student to understand the atomic processes, a provisional model of the atom is described in the first chapter. The actual structure of the atomic core is at present unknown, but if it is assumed to consist of a stable electron vortex associated with a positive charge, the reactions of the atom can be explained in a fairly simple manner.

The attempt which has been made in these pages to describe present-day wireless apparatus and instruments falls short of this object to the extent that, as the present time is one of rapid transition, the apparatus in use when these descriptions were written—whether appertaining to arc, H.F. alternator, valve, or direction finder—are nearly all in process of being superseded by improved types. The examples given, however, serve to illustrate the theoretical circuits discussed.

As accurate knowledge is conditional on measurement, and the training of the radio worker is not complete without a course in practical testing, the elements of testing have been given liberal space in this book.

The author's acknowledgments are due to Mr. A. M. Young and to Mr. S. J. Willis for the excellent manner in which they have prepared the numerous line drawings required; to Marconi's Wireless Telegraph Company, Ltd., for the photographs of instruments; and also to Mr. W. H. Nottage, B.Sc., for a helpful criticism of the completed book.

H. M. DOWSETT.

Marconi Works,
Chelmsford,
1920.

CONTENTS

CHAPTER I

PAGE
THE NATURE OF ELECTRICITY AND OF THE ATOM . . . 1

The Electron; the Negative Charge; the Positive Charge; the Ion.—An Electric Current in a Solid Conductor; in a Liquid; in a Gas.—The Atom, its Structure and Reactions.—Properties of the Atom.—Atomic Models of J. J. Thomson, E. Rutherford, N. Bohr, G. W. Nicholson.—The Electron-Vortex Atom; its Flexibility and Stability.—The Formation of the Secondary Group of Electrons; the Number in it; the Magnetic States of the Atom; the Process of Ionisation; the Dispersion of Bombarding Electrons; the Cause of Light; X-Rays; Radio-Activity; the Birth of a Helium Atom.—Chemical Action; Electrochemical Dissociation.—Relative Sizes of some Atoms.

CHAPTER II

ON PHASE DISPLACEMENT EFFECTS IN ELEMENTARY CIRCUITS . 17

The Ether, and the Magnetic Field.—The Current along a Conductor, the Magnetic Field which accompanies it and the Generation of Back E.M.F.—The Advantage of a Solenoid.—The Magnetic Fields due to Straight, Bent, and Re-entrant Solenoids.—The Effect of adding an Iron Core.—The Phase Relationship of the E.M.F. required to drive a Current through a Circuit containing Resistance, Inductance; both Resistance and Inductance.—The Electrostatic Field of a Condenser; its Back E.M.F.; the Effect of a Direct Current Charge, and Independent Discharge.—A Condenser charged by an Alternating E.M.F.; the Phase Displacement due to Resistance in the Condenser Circuit.—A Circuit containing Capacity and Inductance subjected to a Short Application of a Steady E.M.F.—An Oscillatory Charge and Discharge following a Short Application of a Steady E.M.F.; Electromagnetic Radiation; the Conditions for Resonance in an Alternating Current Circuit.—The Effect on an Alternator of a Difference of Phase between the Current through its Windings and the Generated E.M.F.—The Limiting Power of an Alternator.—The Use of a Transformer to charge a Transmitting

PAGE

Condenser.—The Transformation Ratio; Phase Relationships in a Transformer.—The Magnitude Relationships of Current, E.M.F., Resistance, Inductance, and Capacity, in the Transformer Primary and Secondary Circuits.—Vector Quantities, and Vector Diagrams. —Current, and Potential Vectors.—Transformer Vector Diagrams for "No Load," "Non-Inductive Load," and "Capacity Load." —The Phase Effects of Magnetic Leakage.

CHAPTER III

THE SPARK DISCHARGE 44

A Common Method of starting an Oscillatory Current.—Amplification of Current and Condenser P.D. due to Resonance.—The Condenser Discharge Circuit.—The Timing of the Discharge; the Factors which should determine it; the Paths open to the Discharge. —The Resistance of the Gap; Discharge when the Main Current is falling.—The Condition of the Gases in the Spark Gap —Necessity for Metallic Vapour.—Relation of Gap Conductivity to Power in the Spark; Resonance in relation to Spark Discharge.—Resonance when Sparking; Conditions required.—The Case for the Leading Charging Current, and for the Lagging Charging Current.—The Lagging Effect of the Discharge; the Phase at which the Spark Discharge should be taken, varies with the Conditions of each Circuit.—The most Efficient Type of Charging Circuit.—The Principle of the Marconi Disc Discharger.—The Scale of Spark Phase.—What it indicates; the Burning of the Electrodes by the Spark; the Use of Disc Electrodes.—The Effect of Windage.—The Arc at Break; the Importance of the Time of Interruption of the Spark.—The Marconi-Mackie Disc Discharger.—The Calibration of the Disc Discharger for Spark Phase.—The Use of a Telephone; Milliammeter; Transformer and Disc Discharger.—To adjust the Spark Phase.—The Best Audible Note.—The Plain Discharger.—The Use of Leading or Lagging Current.—The "Quenched-Spark" Discharge.—Coupled Circuit Reactions.—The Effect of strongly damping the Oscillations in the Condenser Circuit.—Shock Excitation; the Telefunken Type of Gap.—The Marconi Type; the Effect of de-tuning the Aerial Circuit; the Effect on the Tuning of increasing the Power applied to the Gap.

CHAPTER IV

CONTINUOUS WAVE TRANSMITTERS 70

The High-Frequency Alternator.—Its Working Range of Frequency.—Two General Types of Low-Frequency Alternator.—The Design Limitations on Frequency.—The Duddell 2000-Cycle Alternator.—The Alexanderson 100,000-Cycle Alternator.—The Principle on which it works.—Definition of an "Inductor."—Cross-Section

PAGE

through the Machine.—Relation of Armature Winding to Inductor Spokes.—The Step-up Gear.—The Bearings.—Electrical Constants of the Machine.—Scheme of Connections to the Aerial.—Correction for Speed Variation.—Stator Winding of Alexanderson 200,000-Cycle Alternator.—The H.F. Alternator of the Société Française Radio-Electrique.—General Description.—The Goldschmidt Alternator.—Principle on which it works.—The same Principle active in Standard L.F. Alternators, but not encouraged.—The Phase Relationships of the Currents of *n*, 2*n*, 3*n*, and 4*n* Cycles in the Stator and Rotor Windings.—Comparable with Conditions in a Static Transformer.—Losses Accumulative with Increase of Frequency.—The H.F. Alternator at Hanover.—Scheme of Connections to the Aerial; for 40,000 Cycles; for 60,000 Cycles.—Static Frequency Changers.—The Magnetisation of Iron; by Direct Current; by Alternating Current.—Hysteresis.—Direct and Alternating Currents through separate Windings on the same Iron Core.—Current and Flux Curves.—Method of Vallauri and M. Joly for Doubling the Frequency.—Transformer Connections.—Current, Flux, and Potential Curves.—Method of M. Joly for Tripling the Frequency.—Current, Flux, and Potential Curves.—The Marconi "Timed Spark" Method.—Normal Spark Discharge.—The Effect of superposing Wave-Trains which are out of Step; the Oscillations in the Separate Trains being maintained in Step.—The "Trigger Spark" Method of Timing.—A "Timed Spark" C.W. Transmitter with one Disc and four Discharge Circuits.—Four Discs in Series in each of four Circuits for High Discharge Voltages.—The Arc Transmitter.—The Duddell Arc.—Similarity of the Arc and Condenser Characteristics; Suggested Method of Operation of the Duddell Arc.—The "Static" and "Dynamic" Characteristics of an Arc.—The Duddell Arc Current.—The Duddell Arc Characteristics.—Range of Frequency and Efficiency.—The Improvements introduced by V. Poulsen.—Air and Hydrogen Arcs.—The Poulsen Arc Current and Potential Curves.—The Poulsen Arc Working Characteristic.—The Effect of the Magnetic Field on the Arc.—The Poulsen Arc.—Aerial Connections.—The Method of Signalling with an Arc Transmitter.—The Marconi Expansion Chamber.—A 25-kw. Marconi-Poulsen Arc Transmitter.—The Valve Oscillator.

CHAPTER V

THERMO-IONIC EFFECTS AND OSCILLATION VALVE PHENOMENA . 106

The Electrical State of Materials at High Temperatures.—The Effect of High Temperature on the Atom.—The Interchange of Electrons between Atoms in a Conductor at High Temperature.—The Oscillation Valve of J. A. Fleming.—Its Rectification Effect.—The Valve Saturation Current.—The Plate Characteristic.—The Effect of increasing the Filament Temperature on the Characteristic.—Method of increasing the Rectification Effect.—The Three-Electrode Valve.—The Control Action of the Grid.—Space Charge.—The Ampli-

PAGE

fication Effect.—Grid-Plate, Characteristics.—The Use of different Parts of the Characteristics.—The Effect of altering the Filament Current of the Three-Electrode Valve.—The Filament sometimes connected to the Positive End of the Heating Battery.—The Operation of an Amplifier Circuit.—High-Frequency Amplification.—Low-Frequency Amplification.—The Efficiency of Rectification.—The Retro-Active Effect.—The Reaction Coil.—Simple and Cumulative Rectification.—The Production of Continuous Waves by an Oscillating Valve.—The Effect of a Condenser in Shunt to a D.C. Generator which has a Rippled Wave-Form.—The Reception of Continuous Waves.—The Production of "Beats."—A Valve "Self-Beat," or "Self-Heterodyne" Circuit.—The Oscillating-Valve Telephone Transmitter.—The Use of A.C. Generators for Valve Circuits.—Types of Three-Electrode Valve.—Marconi Valve Instruments.—Receiver, Type No. 27.—Field Station Receiver, Type No. 38*a*.—Amplifier, Type No. 55.—Multiple Tuner used with Amplifier, Type No. 55.—Multiple Tuner, Magnetic Detector, and Note Amplifier.—Note Amplifier for Use with either Magnetic or Crystal Detector.—Short-Distance Wireless Telephone Transmitter and Receiver.—Short-Distance Wireless Telephone Set, Type T.T. 2.—Wireless Telegraph and Telephone Set, Type T.T. 3.

CHAPTER VI

THE SPECIAL APPARATUS USED FOR HIGH-SPEED TRANSMISSION AND RECEPTION 150

Transmitting Apparatus.—The Air Compressor and Reservoir.—The Creed Relay and Air Engine.—The High-Tension Signalling Switch.—The Wheatstone Transmitter.—The Wheatstone Perforator.—Dictaphone Reception.—Dictaphone Cylinder Shaving Machine.—The Einthoven Galvanometer Recording Set.—The Marconi-Einthoven Photographic Outfit.

CHAPTER VII

THE MEASUREMENT OF ELECTRIC CURRENT AND OF ELECTROMOTIVE FORCE 162

The Unit of Current.—The Kelvin Balance.—Galvanometers.—"Factor of Merit."—The D'Arsonval Type.—"Dead-Beat" and "Ballistic" Movements.—The Thomson Astatic Galvanometer.—The Thermo-Electric Effect.—The Duddell Thermo-Galvanometer.—The Duddell Oscillograph.—The Drysdale-Tinsley Vibration Galvanometer.—The Einthoven String Galvanometer.—The Measurement of Electromotive Force.—The Definition of the Volt.—The Clark Cell.—The Weston Cadmium Cell.—The Potentiometer.—Its Adjust-

PAGE

ment.—The Measurement of P.D. across a Resistance.—The Calibration of an Ammeter; of a Galvanometer; of a Low-Tension Voltmeter.—Commercial Potentiometers. — The Quadrant Electrometer.—The Original Thomson Instrument.—The Dolezalek Electrometer. — The Measurement of High Potentials. — Current and Potential Indicating Instruments. — Ammeters. — Voltmeters. — Similarity of Design.—The Division of Electromagnetic Instruments into Three Groups. —The Moving Coil Principle.— The Average Current Indication.—The Dynamometer Principle.—The R.M.S. Current Indication.—Soft Iron Ammeters.—The Everett-Edgecumbe Model.—The Weston Model.—Thermo-Ammeters. –The Hartmann and Braun Hot-Wire Type.—Methods of increasing the Current-carrying Capacity of the Expanding Wire. — A Hartmann and Braun so-called "Shuntless" Ammeter. — The Duddell Thermo-Ammeter.—Parallel Wire Ammeters with Thermo-Junctions.—The Marconi-Ewen Ammeter for Small Currents.— The Marconi-Ewen Ammeter for Heavy Currents,—Air-Core Current Transformers.—The Electrostatic Voltmeter.—For Medium Voltages.—The Kelvin Volt Balance.

CHAPTER VIII

THE MEASUREMENT OF RESISTANCE 188

Steady Current Resistance.—The "Ohm."—Large Current Sub-Standards.—The Wheatstone Bridge.—The Slide-Wire Bridge.—The Plug Bridge.—The Post Office Pattern.— Method of using the Bridge. —Portable Bridge with Paul Galvanometer.—The Measurement of very Small Resistances.—The Potentiometer Method.—The "Ducter Potential Ohmmeter."—The Ohmmeter.—Resistances of 1 Megohm and above.—Insulation Resistances.—The "Guard Wire."—The "Megger."—Insulation and Dielectric Resistances of Millions of Megohms.—The Use of a Ballistic Galvanometer; of an Electrometer.

CHAPTER IX

THE MEASUREMENT OF CAPACITY 200

The "Farad."—The Electrostatic Unit.—Specific Inductive Capacity.—Capacity by Direct Charge.—The Fleming-Clinton Commutator.—Circuit Connections.—The Capacity Bridge.—The Calibration of Marconi Glass Condenser Tubes.—Residual Charge.—Alternating-Current Measurement of Capacity.—The High-Frequency Resonance Method for Small Capacities.—The Effective Capacity of an Aerial.

CHAPTER X

PAGE
THE MEASUREMENT OF INDUCTANCE 211

The "Henry."—The Anderson Bridge Method.—The Anderson-Fleming Bridge.—The Fleming-Clifton Commutator used with Inductance Bridge.—Slide-Wire Inductance Bridge.—Inductance Bridge with two Sliders.—Slide-Wire Bridge calibrated in Inductance Units.—The "Drop in Potential" Power Method.—The Inductance of a Transformer; of an Alternator.—A Resonance Method for Inductances of several hundred Henrys.—The Harmonic Effects in the Resonance Method.—A High-Frequency Method for small Inductances of a few Microhenrys.—The Unknown Inductance inserted in a Wave-Meter Circuit.—The Effective Inductance of an Aerial.—The Measurement of Mutual Inductance.—The Campbell Variable Mutual Standard.—Coupled Circuits.—The Coefficient of Coupling.—Its Significance.

CHAPTER XI

THE MEASUREMENT OF FREQUENCY 223

Machine Frequencies.—The Frahms Method.—Stroboscopic Methods.—Drysdale's Roller Stroboscope.—A Tuning-Fork controlled Shutter.—The Frequency of Alternating Currents.—The Hartmann and Braun Frequency-Meter.—Method used to double its Range.—The Principle of Induction Frequency-Meters.—The Westinghouse Instrument.—The Weston Instrument.—The Use of a Thin Filament Lamp, or Neon Tube.—An Oscillograph Method.—A Gehreke Oscilloscope Method.—The Behaviour of Frequency-Meters when the Alternations are not Sinoidal.—Spark Frequency.—Fleming Tape Record Device.—The Marconi Dictaphone Method.—Fleming Photographic Method.—The Measurement of Oscillation Frequency.—The Campbell Spark Counter.—Maxwell Bridge Method for indicating any Change in Speed of Revolving Mirror.—Roller Stroboscope and Tuning-Fork Control.—Photographs of Spark Trains.—The Measurement of Wave-Length.—With Reference to a Standard Velocity of Propagation.—"Lecher Wire" Circuits.—The Commercial Wave-Meter.—Wave-Meter Calibration for Short Wave-Lengths up to 300 Metres.—Wave-Lengths of 300 Metres to 1500 Metres, and of 1000 Metres to 3000 Metres.—The Spark-Counter Method best for all Wave-Lengths above 1500 Metres.—Buzzer Oscillating Circuits for Test Room Use.—The Tuning Tester.—A Comparison of the Resonance Method with the Spark-Counter Method when there are Coupled Waves in the Oscillating Circuit.

CHAPTER XII

PAGE
THE MEASUREMENT OF DIELECTRIC STRENGTH 248

The Factors which determine the Dielectric Strength of a Material. —The Effect of Wave-Form.—High Frequency best for testing Surface, Low Frequency for testing through the Thickness.—Dielectric Hysteresis.—The Measure of Dielectric Strength.—Tests for Raw Materials.—Paints and Varnishes.—The Regulation of the Testing Potential.—Paper, Mica, etc.—The Prevention of Brush Discharge from the Edge of the Testing Electrodes.—The N.P.L. Dielectric Strength Test for Ebonite.—Glass Plate Testing.—Spark Voltages. —The Electrostatic Field between Electrodes of different Shapes.—Tube Dielectrics.—Oil Dielectrics.—The Digby Oil Tester.—Table of Dielectric Strengths.—The Testing of Finished Apparatus.—The Duration of the "Presure" Test. —Standard Tests.—For Generators and Motors.—For Transformers.—Windings subjected to both L.F. and H.F. Potential Strains.—The Testing of Condensers.—The most Efficient Form of Condenser has the Conductors embedded in the Dielectric.—The Breakdown of Composite Dielectrics.—The "Rendahl" Condenser Plate.—To remove Moisture from Oil.—The Testing Voltage best obtained from a Source of Power.—The Conditions of Service of a Block Condenser in a Transmitting Aerial Circuit.—An H.F. and H.T. Testing Circuit.—The Maximum Testing Voltage of the Circuit.—The Power required for H.T. Testing.—Aerial Insulators.—The 3-ft. "Flexible" Type.—The 3-ft. "Turnbull" Type. —The "Walnut" Stay Insulator.—The "Semi-Flexible" Stay Insulator.—The Stress in Insulating Bushings.—The Use of a Guard Point.—The Use of Guard Plates.—A Correctly-designed Bush Insulator.—The Effect of Corrugation on Surface Insulation.

CHAPTER XIII

THE MEASUREMENT OF DECREMENT 280

The Swinging Pendulum.—Damping.—An Exponential Curve. —The Logarithmic Decrement.—The Energy which must be given to the Pendulum.—The Ballistic Galvanometer.—Method of finding the Correction for Damping.—The Case of a Simple Form of Non-Sparking Oscillatory Circuit.—The Joulean Decrement.—Spark Resistance.—Lineal Decrement.—Total Decrement of a Circuit containing a Spark.—The Decrements of Coupled Circuits.—The "Degree of Coupling."—Percentage Coupling.—When neither Circuit contains a Spark Gap.—When one or both Circuits contain a Spark Gap.—The Secondary Oscillation when the Primary Oscillation is (1) Slightly Damped; (2) Strongly Damped.—Decrement Measurement from Tuning Curve.—Method of V. Bjerknes.—Method of mis-tuning until Wave-Meter Current falls to half its Value at

PAGE

Resonance.—The Marconi Decremeter.—Theory of Working.—The Instrument Decrement.—The Use of a Resistance for measuring the Instrument Decrement.—Decremeter for very long Wave-Lengths.—Damping in the Aerial Circuit.—To measure the Effective Resistance of the Aerial.—Earth Resistance.—Radiation Decrement.—Current Distribution in an Aerial.—Energy radiated from an Aerial.

CHAPTER XIV

THE MEASUREMENT OF THE DIRECTION, AND THE DISTANCE OF TRANSMITTING STATIONS, AND THE INTENSITY OF RECEIVED SIGNALS 302

The Directional Effect of certain Aerials.—The Marconi-Bellini-Tosi Method of Direction Finding.—As applied to Ship Stations.—The Working Theory.—The Practical Operation of the D.F. Set.—Causes of Error.—The Distance of the Transmitting Station.—D.F. Land Sets.—D.F. Set with Rotary Frame Aerial.—The Measurement of Audibility.—Definitions of Audio Current, Audibility, and Audibility Current.—The Resistance and Reactance of the Telephone.—Comparative Audibilities.—The Relation between the Aerial Current received and the Audio Current, for both Spark and C.W. Signals.

INDEX 325

ILLUSTRATIONS

FIG. PAGE

A Marconi 60-kw. Spark Transmitting Set . . . *Frontispiece*

Table of Symbols xxxi

1. The Electrostatic Field of an Electron . . . 2

2. The Electron Vortex Atom 7

3. The Trapping of an Electron by a positively charged Atom (I.) 8

4. The Trapping of an Electron by a positively charged Atom (II.) 9

5. The Translational Motion of an Atom 11

6. A Negative Ion (*a*). A Positive Ion (*b*) 11

7. The Radio-Active Generation of a Helium Atom . . . 13

8. Chemical Combination 14

9. Electro-Chemical Dissociation 15

10. The Relative Sizes of some Atoms 16

11. Model illustrating the Generation of a Magnetic Field . . 18

12. The Relation between the Current in a Conductor and the Magnetic Field and Back E.M.F. in the Surrounding Space 21

13. The Magnetic Field of a Solenoid 23

14. The Linking of the Lines due to each Turn in the Solenoid . 23

15. The Magnetic Fields of Bent and Re-entrant Solenoids . . 24

16. The Effect of Iron in a Solenoid 25

17. Alternating Current and Potential Curves for a Circuit containing Inductance only 26

18. Alternating Current and Potential Curves for a Circuit containing Inductance and Resistance 26

19. The Electrostatic Field of a Condenser 27

20. The Current and Potential Curves of a Condenser charged by a Steady E.M.F. and then discharged 27

FIG. PAGE
21. The Current and Potential Curves of a Condenser Circuit charged by an Alternating E.M.F. 28
22. The Current and Potential Curves of a Condenser Circuit containing Resistance, charged by an Alternating E.M.F. . 28
23. The Charge and Discharge Curves of a Circuit containing both Inductance and Capacity, and excited by a Steady E.F.M. 29
24. An Oscillatory Charge and Discharge 30
25. Electromagnetic Radiation from an Oscillatory Circuit . 31
26. The Conditions for Resonance in an Alternating Current Circuit 32
27. The Transmitting Condenser connected in Circuit through a Transformer 34
28. An Explanatory Vector Diagram 37
29. Vector Diagrams involving Inductance, Capacitance, and Resistance Quantities 38
30. A Transformer "No Load" Vector Diagram . . . 40
31. A Transformer "Non-Inductive Load" Vector Diagram . 41
32. A Transformer "Capacity Load" Vector Diagram . . 42
33. Magnetic Leakage in a Transformer 43
34. The Amplification of Current and Condenser P.D. due to Resonance 45
35. The Transmitting Condenser Charge and Discharge Circuits . 45
36. Spark Discharge each Half Cycle at Zero Charging Current . 46
37. Resonance Conditions during Discharge 50
38*a*. The Lagging Effect of Spark Discharge 51
38*b*. Oscillograms of H.T. L.F. Current and Voltage when the Spark is taken before the Current reaches Zero . . 52
39. The Principle of the Marconi Disc Discharger . . . 53
40. Scale of Spark Phase 55
41. The Burning Action of the Spark on the Electrodes . . 56
42. The Spark on "Make" and the Arc on "Break" . . . 56
43. The Marconi-Mackie Disc Discharger 58
44. The Discharge Conditions across a Fixed Gap . . . 62
45. The Coupling of a Radiating Circuit to the Condenser Discharge Circuit 64

FIG. PAGE
46. Slightly Damped Oscillations in two Tuned Coupled Circuits 64
47. The Effect of Strongly Damping the Oscillations in one of the two Coupled Circuits 65
48. The Telefunken Type of Quenching Gap 66
49. The Marconi Quenched-Spark Discharger 67
50. The Effect of De-tuning the Aerial Circuit 68
51. The Effect of increasing the Power in the Condenser Circuit . 69
52. Two Forms of Low-Frequency Alternator 71
53. The Duddell 2000-Cycle Alternator 73
54. The Principle of the Alexanderson High-Frequency Alternator 74
55. The Alexanderson 100,000-Cycle Alternator in cross-section . 76
56. The Alexanderson 100,000-Cycle Alternator: Relation of Armature Winding to Stator Spokes 77
57. The Alexanderson 100,000-Cycle Alternator: View of Set complete—Motor, Gear Box, and Alternator . . . 77
58. The Alexanderson 100,000-Cycle Alternator: Scheme of Alternator—Aerial Connections 78
59. Alexanderson 200,000-Cycle Alternator: Relation of Armature Winding to Stator Spokes 79
60. H.F. Alternator of the Société Française Radio-Electrique. 25 kw. 30,000 Cycles 80
61. The Goldschmidt H.F. Alternator 84
62. The Goldschmidt H.F. Alternator: Scheme of Alternator—Aerial Connections 87
63. Static Frequency Changers: the Magnetisation Effects in Iron of Direct and Alternating Currents (I.) 88
64. Static Frequency Changers: the Magnetisation Effects in Iron of Direct and Alternating Currents (II.) 89
65. The Double-Frequency Changer of Vallauri and M. Joly: Transformer Connections 90
66. The Double-Frequency Changer of Vallauri and M. Joly: Current, Flux, and Potential Curves 90
67. The Triple-Frequency Changer of M. Joly: Transformer Connections 91

FIG. PAGE
68. The Triple-Frequency Changer of M. Joly: Current, Flux, and Potential Curves 91
69. The Relation of Sparking Period to Non-Sparking Period for a Synchronous Spark Discharge 92
70. The Marconi "Timed-Spark" Method of producing Continuous Oscillations 93
71. The Marconi "Timed-Spark" Method: (*a*) One Disc used with four Discharge Circuits. (*b*) Four Discs in Series in each Discharge Circuit. 95
72. The "Static Characteristic" of an Arc 97
73. The "Dynamic Characteristic" of an Arc 97
74. The Duddell Arc Current 98
75. The Duddell Arc: its Static and Dynamic Characteristics . 98
76. Arcs in Air and Hydrogen: Static Characteristics . . 99
77. The Poulsen Arc: Current and Potential Curves . . . 100
78. The Poulsen Arc: its Dynamic Characteristic under Working Conditions 101
79. The Arc-Aerial Connections of a Poulsen Arc, showing Marconi Expansion Chamber 102
80*a*. A 25-kw. Marconi-Poulsen Arc Transmitter: Elevation . 103
80*b*. A 25-kw. Marconi-Poulsen Arc Transmitter: Plan . . 104
81. The Effect of Increase of Temperature on the Movement of the Secondary Electrons in the Atom 107
82. Atoms interchanging Secondary Electrons 108
83. The Electrical State of a Glowing Conductor . . . 108
84. The Two-Electrode Valve of J. A. Fleming 109
85. Test Circuit and Plate Characteristic of Two-Electrode Valve. 110
86. Circuit Connections for taking Two-Electrode Valve Characteristics at different Values of Filament Current . . . 111
87. The Plate Potentiometer 112
88. The Three-Electrode Valve Circuits 112
89. Three-Electrode Valve compared against a Two-Electrode Valve for Sensitivity 115
90. Grid-Plate Characteristics, at different Plate Voltages . . 115

FIG. PAGE
91. The Effect of altering the Filament Current on the Grid-Plate Characteristic 117
92. The Filament connected to the Positive End of the Heating Battery 117
93. Low-Frequency Amplification 118
94. Comparison of Rectification obtainable with Small and Large E.M.F. 119
95. The Use of a Reaction Coil 121
96. Simple Rectification 122
97. Cumulative Rectification 123
98. A Three-Electrode Valve Circuit for the Generation of Continuous Waves 124
99. A Valve Oscillator coupled to an Aerial 124
100. A Simplified Form of Valve Oscillator Circuit . . . 125
101. A High-Tension Generator used in place of a Plate Circuit Battery 125
102. Oscillograms showing the Effect of a Condenser on a Fluctuating Direct Current Supply 126
103. The Rectification of Continuous Oscillations . . . 126
104. Two Sets of Continuous Oscillations of different Frequency employed to produce a Beat Frequency 127
105. An Arrangement of Circuits employing a separate Generator to produce a Beat Note 128
106. A Valve Circuit arranged as a Self-Beat Generator and Detector 128
107. A Valve Telephone Transmitter, with Microphone in the Aerial Circuit 129
108. A Valve Telephone Transmitter, with Microphone arranged to affect the Grid Circuit 129
109. An A.C. Generator employed with a Valve Telephone Transmitter 130
110. Types of Three-Electrode Valve 132
111. Marconi Receiver, Type No. 27. General View . . 133
112. Marconi Receiver, Type No. 27. (a) Plan of Top of Instru-

FIG. PAGE
ment. (*b*) Scheme of Connections for receiving Spark Signals. (*c*) Scheme of Connections for receiving Continuous Waves 134
113. Marconi Field Station Receiver, Type No. 38 (*a*): General View 136
114. Marconi Field Station Receiver, Type No. 38 (*a*): Scheme of Connections 136
115. Marconi Field Station Receiver, Type No. 38 (*a*): the Three Valve Working Characteristics 137
116. Marconi Valve Amplifier, Type No. 55: General View . 138
117. Marconi Valve Amplifier, Type No. 55: Scheme of Connections 139
118. Marconi Valve Amplifier, Type No. 55: Internal View of Fittings 140
119. Multiple Tuner and Valve Amplifier, No. 55: External Connections 140
120. Multiple Tuner and Valve Amplifier, No. 55: Internal Connections 140
121. Multiple Tuner, Magnetic Detector, and Note Amplifier: External Connections 141
122. Multiple Tuner, Magnetic Detector, and Note Amplifier: Internal Connections 141
123. Note Amplifier for Use with either Magnetic or Crystal Detector: Internal Connection 142
124. Marconi Short-Distance Wireless Telephone Transmitter and Receiver: General View 143
125. Marconi Short-Distance Wireless Telephone Transmitter and Receiver: Internal Scheme of Connections . . . 144
126. Marconi Short-Distance Wireless Telephone Transmitter and Receiver: External Scheme of Connections 145
127. Marconi Short-Distance Wireless Telephone Set, Type No. T.T. 2: General View 145
128. Marconi Short-Distance Wireless Telephone Set, Type No. T.T. 2: Internal Fittings 145
129. Marconi Short-Distance Wireless Telephone Set, Type No. T.T. 2: Scheme of Connections 146

FIG. PAGE
130. Marconi Wireless Telegraph and Telephone Set, Type T.T. 3 : General View 147
131. Marconi Wireless Telegraph and Telephone Set, Type T.T. 3 : Scheme of Connections 148
132. Connection Diagram of Wheatstone Transmitter to Creed Air Engine Relay 150
133. General Arrangement of Plant for working High-Tension Signalling Switch at High Speed 151
134. View of High-Tension Signalling Switch and Air Engine . 152
135. Four-Way Motor Blower 153
136. View of Wheatstone Transmitter with Driving Motor . . 153
137. Wheatstone Transmitter Contacts 154
138. Wheatstone Transmitter : Sample of Punched Slip . . 154
139. Wheatstone Transmitter : Method of working . . . 154
140. Wheatstone Transmitter : Connection Diagrams . . 155
141. Wheatstone Transmitter : Motor Control Diagram . . 155
142. View of Wheatstone Perforator 156
143. Wheatstone Perforator : its Principle of working . . 156
144. Connection Diagram for Dictaphone Reception . . . 157
145. View of Dictaphone 157
146. Two Dictaphones with Telephones connected in Series . 158
147. Einthoven Galvanometer Recording Set : the Optical System 160
148. View of Marconi-Einthoven Photographic Recording Cabinet 161
149. The Kelvin Ampere Balance : Principle of Action . . 163
150. View of Kelvin Ampere Balance 164
151. (*a*) The D'Arsonval Galvanometer. (*b*) and (*c*) The Shape of its Magnet Poles 165
152. The Damping of Galvanometer Movements 166
153. The Thomson Astatic Galvanometer 167
154. The Thermo-Electric Power of Various Metals . . . 168
155. The Duddell Thermo-Galvanometer 168
156. The Duddell Oscillograph Galvanometer 169
157. The Drysdale-Tinsley Vibration Galvanometer . . . 170
158. The Einthoven String Galvanometer 171

FIG. PAGE
159. The Weston Cadmium Cell 173
160. Simple Potentiometer Circuit 173
161. Galvanometer Calibration by Potentiometer . . . 174
162. Voltmeter Calibration by Potentiometer 175
163. (*a*) The Quadrant Electrometer 176
163. (*b*) and (*c*) Electrometer Connections for measuring Low and High Potentials 177
164. The Moving Coil Ammeter 179
165. Alternating, and Variable Direct Current 179
166. The Dynamometer Ammeter 180
167. The Square, Mean Square, and Root-Mean-Square Values of Current 180
168. The Everett-Edgecumbe Soft-Iron Ammeter . . . 181
169. The Weston Soft-Iron Vane Ammeter 181
170. The Hartmann-Braun Hot-Wire Ammeter . . . 182
171. Methods of increasing the Current-carrying Capacity of Hot-Wire Ammeters 183
172. The Hartmann-Braun High-Frequency Ammeter . . 183
173. The Duddell Thermo-Ammeter 184
174. Parallel Wire Ammeters with Thermo-Junctions . . . 184
175. The Marconi-Ewen Ammeter for Small Currents . . 185
176. The Marconi-Ewen Ammeter for Large Currents . . 185
177. An Air-Core Current Transformer used with a Marconi-Ewen Ammeter 186
178. The Electrostatic Voltmeter 187
179. The Kelvin Volt-Balance 187
180. A Resistance Standard of 0·1 Ohm, to carry 15 Amperes . 188
181. The Working Principle of the Wheatstone Bridge . . 189
182. The Slide-Wire Wheatstone Bridge 190
183. Post Office Plug-Bridge: Method of connecting the Coils . 190
184. "Dial" and "Bar" pattern Coil Connections . . . 191
185. Diagram of Post Office Bridge Circuit 191
186. Single Pivot Galvanometer of R.W. Paul, showing Movement 192
187. Fall of Potential Method of measuring Small Resistances . 193

FIG. PAGE
188. The "Ducter Potential Ohmmeter" 194
189. Resistance Measurement by Direct Galvanometer Deflection 195
190. The Use of a Guard Wire for Insulation Tests . . . 196
191. The "Megger" Connections 197
192. Insulation Resistance by "Loss of Charge" Method . . 198
193. "Loss of Charge" Method, using an Electrometer . . 198
194. Capacity by Direct Charge 201
195. The Fleming-Clinton Commutator: the Surface laid out flat 202
196. The Fleming-Clinton Commutator: Sectional View . 203
197. The Fleming-Clinton Commutator: Circuit Connections . 203
198. The Capacity Bridge 204
199. Apparatus used for the Preliminary Calibration before Plating of Marconi Tube Condensers 206
200. Stand used for Check Calibration of Plated Tube Condensers 207
201. Measurement of the Effective Capacity of an Aerial. (*a*) Using Ignition Coil Excitation. (*b*) Using Buzzer Excitation 209
202. The Anderson Inductance Bridge 212
203. The Anderson-Fleming Inductance Bridge 212
204. Fleming-Clinton Commutator for Use with Inductance Bridge 213
205. A Single Slide-Wire Bridge 213
206. A Double Slide-Wire Bridge 214
207. The Power Method of measuring Inductance . . . 215
208. The Variable Inductance of an Alternator 216
209. A Low-Frequency Resonance Method 217
210. The Harmonics which show up in the L.F. Resonance Method 217
211. A High-Frequency Resonance Method 218
212. Measuring the Effective Inductance of an Aerial: (*a*) by means of a Buzzer Method; (*b*) by a Spark Method . 219
213. The Campbell Variable Mutual Standard. (*a*) Diagram showing Arrangement of Coils; (*b*) the Use of the Standard for measuring an Unknown Mutual Inductance . . 221
214. A Stroboscopic Disc and Shutter 224
215. The Drysdale Roller Stroboscope 225

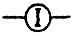
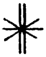
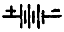
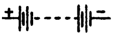
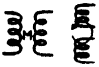
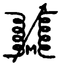
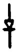
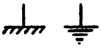
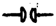
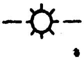
FIG. PAGE
216. An Electrically Controlled Tuning-Fork working a Shutter . 226
217. The Hartmann and Braun Frequency Meter . . . 226
218. The Use of a Direct Current Winding for doubling the Range of a Reed Frequency Meter 227
219. The Principle of Induction Frequency Meters . . . 227
220. The Westinghouse Frequency Meter 228
221. The Weston Frequency Meter 229
222. The Weston Bridge Circuit 229
223. A Full-Scale Oscillogram showing a Current having a Frequency of 4000 Cycles, compared against one of 150 Cycles 230
224. (*a*) Oscillograph and (*b*) Oscilloscope Methods. (*c*) and (*d*) Wave-Forms in a Single Rotating Mirror . . . 231
225. Compound Wave-Form Curves 232
226. A Compound Wave-Form analysed 233
227. A Method of obtaining a Tape Record of Spark Frequency . 234
228. The Marconi Dictaphone Method of obtaining a Spark Record 234
229. The Fleming Photographic Spark Counter 235
230. Diagram illustrating the Type of Record obtained with Fleming Photographic Counter 236
231. The Campbell-Paul Photographic Spark Counter . . 237
232. The Campbell Device for indicating Constancy of Mirror Speed 238
233. The Marconi Method for insuring Accuracy in the Measurement of Mirror Speed 238
234. A Half-Size Reproduction of Three Spark Photographs, the Oscillation Frequencies being 18,790 per sec., 35,375 per sec., and 137,600 per sec. 240
235. The Excitation of a "Lecher Wire" Circuit . . . 242
236. The Wire oscillating at its First Harmonic . . . 242
237. The Calibration of a Wave-Meter from a Lecher Wire . 243
238. The Wire oscillating at its Fundamental Frequency . . 244
239. The Use of a Buzzer Oscillating Circuit for Calibration Purposes 245
240. The Marconi Tuning Tester 245
241. The Two Frequencies due to Tight Coupling . . . 246

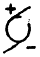
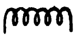
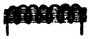
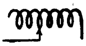
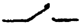
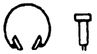
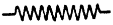
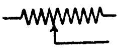
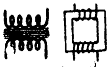
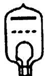
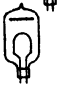
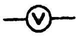
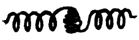
FIG. PAGE
242. The Tight Coupling Curve obtained with a Wave-Meter . 247
243. Four Types of Potential Wave-Form 249
244. Testing a Varnish for Dielectric Strength 252
245. The Variable Potential Testing Circuit 252
246. Flat Electrodes for testing Mica, Paper, etc. 253
247. Wax Moulding to prevent Harmful Brush Discharge . . 253
248. A Recessed Ebonite Plate to take Spherical Electrodes . 254
249. A Glass Plate Testing Pad 255
250. Fittings for Glass Plate Test 255
251. The Electrostatic Field in Air between Surfaces of various Shapes 258
252. Spark Rods with 60° Points 258
253. The Correct Way to use the Spark Gauge 258
254. Electrodes for testing Cylinders 259
255. (*a*) A Tube Test under Oil ; (*b*) a Case in which the Electrodes are very unequal in size 259
256. The Digby Oil Tester 260
257. The Effect of Duration of Test on Breakdown Voltage . 262
258. The Testing of H.F. Protector Chokes 265
259. The "Rendahl" Condenser Plate 268
260. The Condensers in an Arc Circuit 270
261. A Circuit for applying a High-Frequency, High-Tension Test to an Insulator 270
262. Testing a 3-ft. "Flexible" Strain Insulator . . . 273
263. The 3-ft. "Turnbull" Strain Insulator 274
264. Types of Stay Insulators, showing the Electrostatic Fields between the Conductors 275
265. The Electrostatic Field through a Terminal Bushing . . 277
266. (*a*) The Electrostatic Strain relieved by fitting Metal Plates to the Terminal Ends ; (*b*) a correctly designed Bushing 278
267. The Effect on the Field of corrugating the Surface of an Insulator 278
268. The Damping of a Pendulum 281
269. Exponential and Logarithmic Curves of Amplitude . . 281

FIG. PAGE
270. Method of finding the Amplitude of the Undamped Throw of a Ballistic Galvanometer 283
271. Amplitude and Decrement Curves of a Spark Current . . 285
272. Tuning Curves for Weak, Medium, and Tight Coupling . 287
273. The Damping of Oscillations in Coupled Circuits . . 289
274. A Tuning Curve, showing the Method adopted to find the True Resonance Wave-length 291
275. The Co-ordinates of Wave-lengths 4% less and 4% greater than the Resonance Wave-length 291
276. A Simplified Diagram of the Marconi Decremeter . . 292
277. A View of the Marconi Decremeter 295
278. Circuit Diagram of Decremeter with Range 1300 Metres to 9500 Metres 295
279. Circuit Diagram of Decremeter with Range 5000 Metres to 30,000 Metres 296
280. The Aerial "Effective Resistance" Test 298
281. The Distributions of Current in a Simple Aerial, in an Aerial loaded with a large Inductance Coil, and in the Vertical Part of an Umbrella Aerial 300
282. The Directional Effects of an Insulated Horizontal Aerial, a Marconi Bent Aerial, and a Bellini-Tosi Triangular Aerial 303
283. The General Arrangement of a D.F. Set on Board Ship . 304
284. The Ship Type Radiogoniometer Circuit 305
285. A Simple D.F. Receiver Circuit 305
286. The D.F. Tuning Tester 305
287. View of Ship Type Radiogoniometer 307
288. Curve illustrating the Angular Range of Audibility of the Goniometer Search Coil 309
289. Finding the Position of the Transmitting Station by Triangulation 310
290. The Lay-out of Apparatus in a Land D.F. Station . . 312
291. The Buzzer Coupling-Coil Box 313
292. The Buzzer Tuning Tester Board 313

FIG. PAGE
293. The Radiogoniometer of a Land Set 313
294. A Valve Receiver Circuit employing Note Amplification, used in a D.F. Land Set 314
295. The Lay-out of D.F. Land Set which employs H.F. Amplification 315
296. A D.F. Set with Rotary Frame Aerial 316
297. Aerial Change-over Board "Std by" to "Tune" for Quick-search Set 316
298. H.F. Amplifier and Receiver Board for Quick-search Set . 317
299. The Aerial and Receiver Circuit of the Quick-search Set . 317
300. The Telephone Current and the Audio Current . . . 318
301. Diagram of Circuit used for measuring Audibilities by the Shunted Telephone Method 319
302. An Impedance Bridge Circuit 320
303. The Variation of Telephone Resistance and Reactance with Frequency 320
304. Comparative Audibilities by a Potentiometer Method . . 321
305. An Independent Standard Circuit used for measuring the Relation between the Aerial Current and the Audio Current 322

TABLE OF SYMBOLS

Alternator	
Ammeter	
Antenna	
Arc	
Battery, low-tension	
Battery, high-tension	
Condenser	
Condenser, variable	
Coupling, inductive	
Coupling, variable inductive	
Detector, crystal	
Earth	
Gap, spark	
Gap, synchronous spark	

Generator, D.C.	
Inductance	
Inductance, iron core	
Inductance, variable	
Key	
Microphone	
Receivers, telephone	
Resistance	
Resistance, variable	
Transformer, iron core	
Valve, three-electrode	
Valve, two-electrode	
Voltmeter	
Variometer	

Aerial, Amplitude	A
Battery, Magnetic flux density	B
Condenser	C
Dielectric strength	D
Logarithmic decrement	d
Joulean decrement	d_J
Earth, Electromotive force	E
2·7183, Base of Napierian logs.	ε
Filament, Magnetic flux	F
Grid, Galvanometer	G
Field intensity, Magnetising force	H
Ammeter, current	I
Coefficient of coupling	k
Key, Switch, Degree of coupling	K
Inductance	L
Wave-length	λ
Microphone, Mutual inductance	M
Spark frequency	N
Frequency	n
Potentiometer, Primary winding	P
3·14159	π
Resistance	R
Radiation decrement	R_ε
Spark, Secondary winding	S
Periodic time, Telephone, Transformer	T
Time	t
Magnetic permeability	μ
Voltmeter, Voltage	V
Power, Energy	W

WIRELESS TELEGRAPHY AND TELEPHONY

FIRST PRINCIPLES, PRESENT PRACTICE AND TESTING

CHAPTER I

THE NATURE OF ELECTRICITY AND OF THE ATOM

The Electron—The Negative Charge—The Positive Charge—The Ion.—An Electric Current in a Solid Conductor,—in a Liquid,—in a Gas.—The Atom, its Structure and Reactions.—Properties of the Atom.—Atomic Models of J. J. Thomson,—E. Rutherford,—N. Bohr,—G. W. Nicholson.—The Electron-Vortex Atom,—its Flexibility and Stability.—The Formation of the Secondary Group of Electrons—the Number in it,—the Magnetic States of the Atom—the Process of Ionisation—the Dispersion of Bombarding Electrons—the Cause of Light—X-Rays,—Radio-activity,—the Birth of a Helium Atom.—Chemical Action—Electrochemical Dissociation.—Relative Sizes of some Atoms.

The Nature of Electricity.—In *The Handbook of Technical Instruction for Wireless Telegraphists* we spoke of positive and negative electricity, of direct current and alternating current, in fact of electricity in the general terms used to indicate the various well-known forms it assumes in bulk.

But the art of wireless telegraphy draws its inspiration increasingly from the science of molecular physics, which centres round electricity in its elemental form, and we must study it also in this elemental form if we are to obtain a true conception of the actions which take place for instance in the Fleming Valve, or the Crystal Detector, or even in Wave Transmission through the atmosphere.

The historical tests of J. J. Thomson in 1897 definitely established the fact that electricity is granular in structure, it consists of minute particles having the nature of an enormously fine grained gas, $\frac{1}{1835}$th the mass of Hydrogen.

These particles are called "electrons." Each of them carries, or is, an indivisible unit charge of negative electricity. Beyond the fact that the electron is the centre of an electrostatic field, its actual constitution is unknown. It may simply be a strain centre in the ether, similar to a whirl in a fluid. Its field is radial, and evenly distributed all over it, Fig. 1 (*a*), until the electron velocity approaches the speed of light, when theory suggests that the electrostatic lines should leave the poles, or axis of movement, and concentrate towards the equator or plane normal to this axis, Fig. 1 (*b*). A flow past any given point in one direction of 10^{19} electrons per second constitutes a current of one ampere.

Every neutral atom of matter, whether solid, liquid, or gas, carries with it a certain complement of detachable electrons.

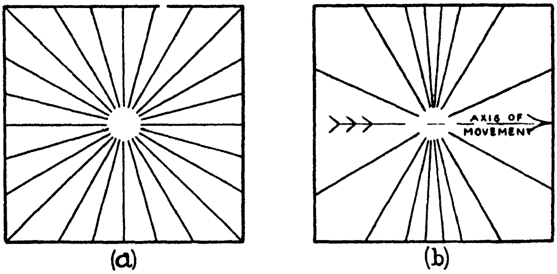


FIG. 1.—The Electrostatic Field of an Electron.

One electron in excess of the correct number gives the atom one unit charge of negative electricity. One electron less than the correct number causes the atom to have one unit charge of positive electricity. The unit of positive electricity has never been separated from the chemical atom. The positive charge appears to be rather a quality than an entity, serving to express the fact that the electrified body has lost one or more negative charges.

Every electrified particle in a liquid or gas has the power to condense other particles round it which are unelectrified, forming a group. Both the single electrified particles and the electrified groups are called "ions." Thus a negative ion may consist of (1) a single electron, (2) an atom with one or more additional electrons attached to it, or (3) a group of atoms having an electron or a negatively charged atom as a nucleus. Also a positive ion may consist of (1) a single atom which has lost one or more electrons, or (2) a group of atoms having a positively charged atom as a nucleus.

The Electric Current.—An electric current in a solid conductor consists of a stream of electrons which is formed as soon as a potential difference is established at two points on the conductor, by simultaneous contributions from a number of atoms scattered along it, the number affected depending on the Electromotive Force applied, the nature of the conductor—whether it is copper or some other metal,—and on the temperature. Under the influence of the potential difference the electrons work their way through the atoms, all in the same direction, from the negative to the positive end of the conductor. On their way they have to pass the atoms which have been robbed of electrons, and which attract them. In consequence, they are continually being captured, while the continued application of the E.M.F. causes a fresh number to be released; and this sequence of operations continues until the E.M.F. is removed, when the electrons are promptly reabsorbed again by the nearest atoms which have been rendered deficient in them, and the current ceases.

When a very low electromotive force such as 0·1 volt is applied to a liquid, the current which results is probably carried entirely by electrons as in the case of a solid conductor, or by free ions which already exist in the liquid; but with certain liquids termed "electrolytes" when the electromotive force exceeds a stated voltage—the critical value varying with the liquid between 0·5 volt and 3·0 volts—chemical dissociation of a number of the molecules takes place, and the current is made up of two streams of ions, one positive, the other negative, moving in opposite directions. The molecules break up into two parts, one part which carries one electron in excess, and another part which carries one electron less than the number required to make each part electrically neutral.

The ions attract neutral molecules and break them up, forming new ions. They combine with the ions of opposite polarity to form new neutral molecules and thereby set free new ions of the same polarity to carry on the process further. In this way the effect is transmitted by the two streams which are constantly being renewed, reabsorbed, and again renewed, the positive ions moving from the anode to the cathode, and the negative from the cathode to the anode.

Conductivity in a gas may either be due to direct electron discharge, the carrying of the charge by electrified particles of floating solids, or to the production of gaseous ions by the break-up of the gas molecules as in electrolytic conduction through a liquid.

Either one or more of these effects may be present, depending entirely on individual conditions. The chemically complete molecules of gases and vapours do not act as current carriers They may condense round electrons or atomic ions, but under the influence of an applied electromotive force their charged nuclei leave them.

The subject of the conductivity of electricity through gases is one of ever-increasing importance, particularly with regard to (1) the elucidation of arc phenomena, and (2) a proper understanding of the rapid developments which have taken place in connection with the thermo-ionic valve; but it can only be studied effectively if an endeavour is made at the same time to obtain as clear an idea as possible of the internal mechanism of the atom.

The Atom. Its Known Properties.—In order to construct a model of the atom which approximates as closely as possible to the actual thing, we must build on the basis provided by all the well-authenticated facts relating to its properties.

Thus it has been definitely established that—

1. The atom contains electrons which are detachable when chemical action takes place, or when an electric current flows through a conductor.

2. The atom exhibits the effect of positive electrification when one or more electrons are taken from it, and of negative electrification when one or more electrons are added to it.

3. When the atom is put into a very rapid state of movement by the application of heat, it gives rise to the light effects of the spectrum—ether vibrations of very high

frequency—which show that it contains electrons moving in some form of harmonic motion, the total resultant of which—as shown by the series of lines in the spectrum—is the same for all atoms of the same chemical element.

4. If the atom is subjected to a violent bombardment by electrons, it sends off intense light waves of very short period and very high damping, known as X-rays, and liberates some high-velocity electrons which normally are not detachable.

5. It possesses some special kind of force, or structure, which prevents these strongly held or "bound" electrons from being set free when the detachable electrons are set free.

6. In the radio-active break-up of the heavy atoms of Radium, Uranium, etc., other lighter atoms besides electrons appear to be expelled, as they put in an appearance a very short time afterwards.

7. The atom has magnetic properties.

Models of the Atom.—It was in 1897 that J. J. Thomson first put forward the suggestion that matter was built up from one form of primordial corpuscle—the electron—and that the whole of the mass of the atom was due to electrons either embedded in, or else held by a positive nucleus; but after further study, and by deduction from several lines of reasoning, the same investigator came to the conclusion, which he published in 1906, that the number of bound electrons in the atom could not be very greatly different from one to three times the atomic weight of the chemical element concerned; the balance of the mass therefore being due to the positive nucleus. Other evidence has since been quoted in support of this conclusion, which is now very generally accepted.

In the Thomson Model there are two distinct parts: (*a*) a dense central mass made up of positive electricity and electrons forming a core, which remains unaffected by chemical changes, and does not enter into the production of light, but is affected by X-rays, and is the source of radio-activity; and (*b*) one, or more, up to eight electrons, revolving in a weaker positive field round this core, which act as the chemical bonds between atoms, determine valency, are displaceable from the atom, and produce light by their vibrations.

The core is divided into parcels of positive electricity, which may be ejected with their bound electrons when the atom is radio-active.

In the model proposed by E. Rutherford, the positive nucleus is of an extremely minute size, much smaller than an electron, and the electrons move round it in orbital motion at different distances and at different angular speeds, in the same way as in the solar system the planets move round the sun.

N. Bohr assumes that the electrons in the atom revolve in circular orbits in the same plane about the positive nucleus, and at distances directly proportional to their speeds. Radiation takes place when an electron falls from its orbit into another concentric to it, its speed being at the same time reduced to that of the electrons in the new orbit.

In the J. W. Nicholson atom, the electrons revolve in a single ring round the nuclei or cores of positive electricity, which are larger than what Rutherford requires, and consist of complex structures of smaller positive nuclei and single electron rings. The vibration of each electron is normal to the plane of its orbit.

These are the principal well-known theories which have all been exhaustively discussed elsewhere. It will be seen that there is considerable divergence between them, so that there is still much scope for speculation as to the true structure of the atom.

Until scientific opinion is more settled on this question, the student may find it helpful to think of the atom as being constructed in the manner now to be described—which was devised by the author some years ago,—particularly as the structure suggested is definite, its simplicity renders it unnecessary to make many assumptions, and its reactions—which can be understood by the non-mathematical mind—will be found to provide simple explanations for most of the electro-atomic processes.

The Electron Vortex Atom.—The formation of the atom is primarily due to the existence in the ether of a zone of high energy density, or *positive potential,* which is brought down to mean energy density and equilibrium by the inflow of a sufficient number of electrons, or negative charges. The total mass of the atom is due to electrons. Unlike the valency electrons of J. J. Thomson and Stark, which are tied in a particular position between the atoms which they link, every electron is in ordered and related motion, and thus is endowed with kinetic energy, which becomes immediately apparent should it for any reason leave the atom.

The electrons are disposed in two main groups, the primary distinction between them being one of speed. In the principal group, which corresponds to the atomic core or positive nucleus of other theories as it limits the zone of positive potential, the electrons are all moving at a very high but variable velocity, which, however, is not sufficiently variable to render them unstable in the group. The shape the electrons give to this group somewhat resembles the ether vortex atom which Kelvin suggested in 1867, as it consists of a series of concentric anchor rings, one within the thickness of the other, rotating round their common axis, Fig. 2. These rings in section show the electrons moving in a series of concentric elliptical orbits.

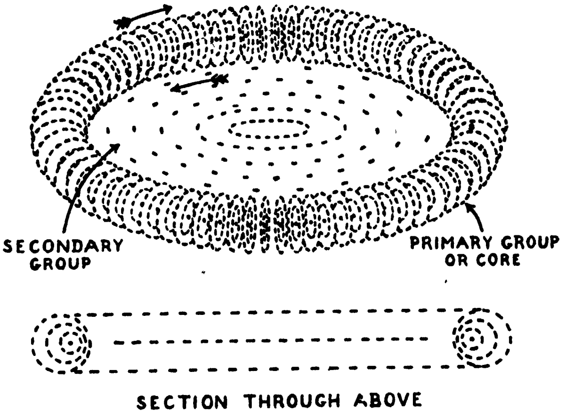


FIG. 2.—The Electron Vortex Atom.

All the rings of a group rotate in the same sense, and all the orbits are in the same sense, and there is a fixed relation between these two directions. This electron vortex ring is flexible, as, according to the ether forces present, the speed of each electron is used partly in translational motion, partly in the vortex motion, and partly in the rotational motion of the ring, which at times necessitates that the electrons shall change their relative places in it; but its internal stability is so great that up to the present it has successfully resisted all analytical methods of investigation, with the result that the only electrons which are now supposed to be in the atom are those which are here described as occurring in the secondary group.

The secondary group consists of a number of low-speed electrons revolving in circular orbits in the aperture of the core, and in the plane of the atom; the lowest in speed at or near the centre, the others at distances therefrom proportional to their velocity.

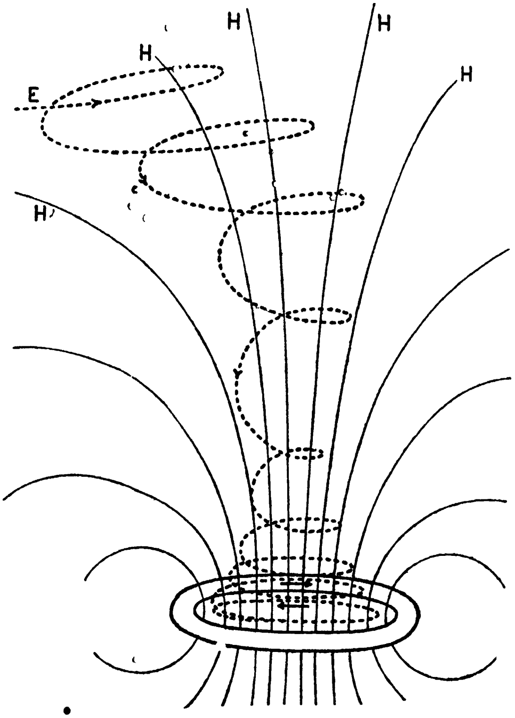


FIG. 3.—The Trapping of an Electron by a positively charged Atom (I.).

All these electrons revolve in the same sense, but in the opposite sense to that of the core.

Atomic Properties and Reactions as explained by the Electron Vortex Theory.—The secondary group is formed in the following manner. The rotation of the core produces a magnetic field H (Fig. 3). Now any free electron, E, of sufficiently low speed passing transversely through this field will be given a spiral movement, which will tend to be parallel to the core, but opposite to its direction of rotation; and although the total speed of the electron will remain the same, its translational speed through the field will be reduced. This will allow the gravitational attraction of the mass of the atom, and any positive electrification associated with the existence of the core, to have greater effect, and the mean path of the electron will bend increasingly towards the atom.

The electron E will thus be brought into a stronger field, and its spiral movement will be increased, until finally the whole of its velocity is turned into orbital velocity in the aperture of the atom, where it remains a prisoner.

Or, take the case of another electron, E$_1$ (Fig. 4), moving almost along the axis of the atom. If the atom has its full complement of secondary electrons, and is therefore *neutral*, the free electron B should be able to pass right through the aperture without being captured; although it may be deviated somewhat from its path, or it may displace a secondary electron from its orbit.

But if the atom has less than its full complement of secondary electrons, it will have an external electromagnetic field, and the smallest deviation of the path of electron E$_1$ from parallelism with the lines of magnetic field will cause it to spiral. The translational movement of the electron will be checked, and finally, if the

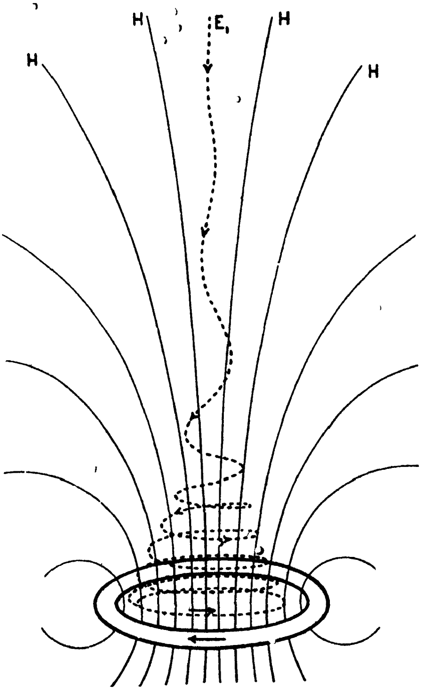


FIG. 4.—The Trapping of an Electron by a positively charged Atom (II.).

field is strong enough, it will be reduced to that of the attracting atom, the balance being turned into orbital motion of the electron within the aperture of the atom.

This operation will be repeated with other free electrons until the whole of the external field of the core, magnetic and electrostatic, has been neutralised by the combined fields of the trapped electrons.

The number of electrons in the secondary group is therefore proportional to the revolutions per second of the core—that is, to its mean diameter—and also to the total number of electrons in the core. It is therefore roughly proportional to —but very much less than—the atomic weight.

The balance of the magnetic fields of the core and the secondary group is not always perfect.

If there is a resultant field—which must be in favour of that of the core—the atom will behave in a *paramagnetic* manner.

A paramagnetic atom sets itself so that its field assists the external field; the field of its secondary electrons will therefore be opposed to the external field and a disturbance of equilibrium will result. In certain cases the speed of rotation of the secondary electrons may be so slow, and their combined field so weak, that the application of an external field destroys their equilibrium altogether, with the result that the external magnetic field of the atom due to the core becomes enormously strengthened, giving rise to the *ferro-magnetic* effect.

If there is a true balance, and therefore no resultant field, the atom will behave in a *diamagnetic* manner and will set itself so as to oppose any applied external field.

The low-speed secondary electrons form the supply from which is drawn the electron streams which give us current phenomena, whose presence in excess constitutes a negative charge on an atom, and whose absence a positive charge.

How such an atom becomes charged or ionised can be explained as follows:—

Owing to the action of gravitation the speeds of the electrons in the core will be greatest at those parts of their orbits which are nearest to the core axis; and any positive electrification associated with the existence of the core will have the same effect. This will cause a neutral atom—that is, one having its correct complement of secondary electrons—to have a translational motion along its axis in the direction given by the electrons on the *inside* diameter of the core; see Fig. 5.

Now suppose we establish an electrostatic field along the axis of a neutral atom. Then, if it is such as to increase the speed of the electrons when they are travelling on the inside diameter of the core, it will oppose them when they are on the outside diameter; the orbital acceleration will be increased and therefore the translational speed of the core. The atom will move in the same direction as an electron under the influence of the same field, from the negative pole or cathode, to the positive pole or anode, and the external field will not tend to displace any of its electrons.

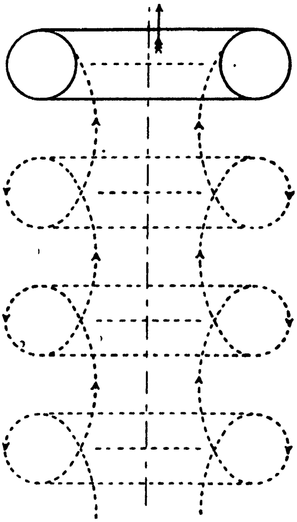


Fig. 5.—The Translational Motion of an Atom.

If an electron moving towards the anode overtakes the atom, it may be captured, as in order to move in the same direction as the electrons in the primary group it will endeavour to pass through the aperture. If this occurs the atom then becomes a *negative ion* (Fig. 6 (*a*)), capable of neutralising a positive charge by the release of the captured electron.

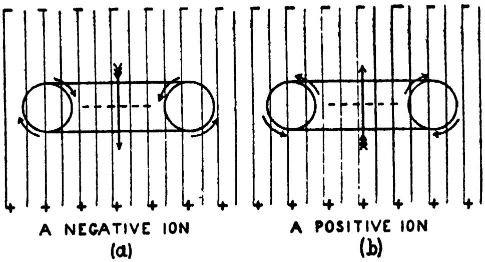


Fig. 6.

But if, on the contrary, the electrostatic field is such as to oppose the motion of the core electrons when they are travelling on the inside diameter, and to assist their motion when they are on the outside, the orbital acceleration of the electrons will be lowered, the translational velocity of the core will fall, free electrons travelling towards the anode will pass outside the core, and as the atom will be moving towards the cathode the field will tend to displace one or more low-speed secondary electrons and send them in the opposite direction. If this takes place, the atom becomes a *positive ion* (Fig. 6 (*b*)), and continues its journey towards the cathode.

If high-speed electrons or cathode rays are projected through the atom, they will suffer dispersion due to the repulsion effects of the secondary electrons which they pass on the way: the amount of dispersion will naturally depend on the number of electrons in this secondary group.

When the core electrons are moving through the core aperture, they are nearer the centre of mass of the atom, which is also the centre of its positive charge, and they therefore move faster than when they are on the outer circumference.

This speed variation of the core electrons generates light waves. As there are many electron rings in the core section, and as each ring in addition to its main acceleration has a distinct series of accelerations induced in it by speed changes in neighbouring rings, the ether waves which result cover a wide range of frequency.

When an atom is bombarded by a stream of high-velocity electrons which its own magnetic field is not strong enough to divert to a narrow enough orbit round the atomic axis, the electrons plunge right into the volume of the core, and an effect equivalent to a collision is produced, although there is no actual contact with the core electrons. For a short time the whole core is set in a state of rapid vibration, thereby creating ether pulses of a very high frequency known as X-rays, which, in contrast to light waves, are highly damped, and therefore do not as readily show the effects of interference and refraction. The impinging electrons are either shot out again at a different angle to that at which they entered the core, or else they displace and replace other high-speed electrons in it.

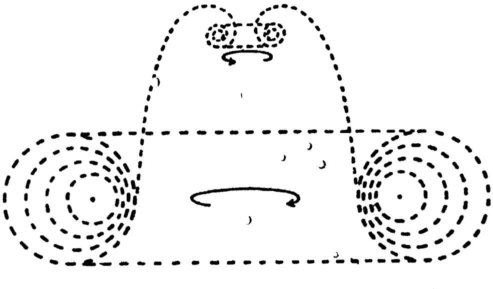
Radio-active effects come from the core. Sometimes they involve such large numbers of electrons that fresh cores are formed, which correspond in all respects to the core of one of the lightest known atoms, Helium.

We can reason this out as follows :—

The stability of the atom is due to a balance of its internal forces; these forces being due to the speed of the electrons, their negative charges which cause mutual repulsion, the positive potential of the space they occupy which holds them together, and their masses which cause gravitational attraction.

Now suppose that for any reason the equilibrium of these forces is disturbed, so that the core is no longer able to hold all the electrons on its outside skin; then this disturbance being felt all round the core, a number of electrons will be simultaneously shot off from it when they reach that position in each of their orbits at which their velocity is greatest—that is, when they are nearest to the core axis.

But their release will render the atom strongly positive, and the pull back into the atom due to this cause will be assisted by the attraction of its mass, and the influence of its external magnetic field which their leaving has tended to increase, and which will cause them to rotate in a direction opposite to that of the old core. If the electrons are numerous enough their own mass will tend to keep them together, and as they all belong to the high-speed type, they will finally curl in again towards the atom (Fig. 7), and will arrange themselves in a new order of stability, part of their speed appearing as rotation in a new core, and part as orbital motion round its section, a fraction of the positive potential of the space occupied by the old core being at the same time surrendered to the new.



SECTION SHEWING RADIO-ACTIVE GENERATION OF HELIUM ATOM

FIG. 7.

The simplest atomic core to construct in this way must undoubtedly be one of those which contain fewest electrons, namely, Hydrogen or Helium. While this process is in operation, the rearrangement of the remaining electrons in the old core is generating X-rays.

Finally, let us consider a simple case of chemical action. When two atoms of different elements which are travelling in opposite directions approach each other, they experience the gravitational attraction of their masses, which is assisted by the electrons on the nearest surfaces of the two cores moving in the same direction, and they will tend to draw together. If there is a large difference between them in diameter, the smaller ones will pass through the larger one; if there is only a small difference, they will approach, and keep in a flexible companionship for a while, until the forces in the medium drive them apart again.

There is, however, an intermediate state, in which the difference in diameter is such that the smaller atom can either just enter the larger one, or else it can be made to do so by means of a forced shrinkage in its own case and an extension in the case of the other.

When this happens, the two atoms hold together and move as one, and the process which brings it about is called *chemical combination.*

In Fig. 8, one of the so-called electro-positive atoms, such as Potassium, Sodium, etc., represented by the core of large diameter, is shown entering into chemical combination with one of the so-called electro-negative atoms, such as Chlorine, Bromine, etc., represented by the core of small diameter.

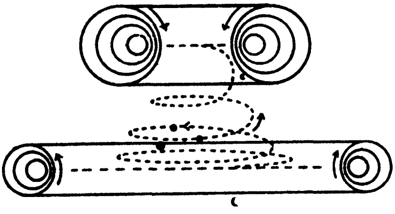


FIG. 8.—Chemical Combination.

The secondary electrons from the core of large diameter are shown at the same time spiralling into the aperture of the small core, where they re-form in orbits with the other secondary electrons.

Each core shrinks in itself, it may be a little or it may be much, due to the increased gravitational and electrostatic effects which result from the combined action of the two masses and their charges; but as they revolve in opposite directions, they keep sufficiently free from each other to maintain their individual existence.

The direction of translation of the newly formed *molecule* is now controlled by that of the more mobile core, the inside one.

If the molecule is to be subjected to electric stress with the object of splitting it up again (Fig. 9), this stress must be applied in the direction which opposes the motion of the inside core, and assists the independent motion of the outside core, so that it rolls forward on the other.

When dissociation takes place, the inside core will therefore leave the outside core on the opposite side to that on which it entered; it will be moving towards the cathode, and in consequence its capacity for holding electrons will be decreased, so that it becomes a *positive ion*, and takes *less* than its normal share of secondary electrons from the molecule; while the outside core, travelling towards the anode, will be assisted by the electrostatic field so that it retains *more* than its normal share of secondary electrons, and thereby becomes a *negative ion*.

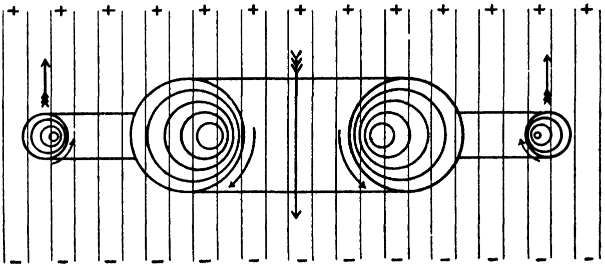
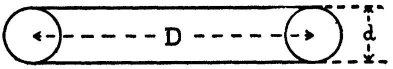


FIG. 9.—Electro-chemical Dissociation.

Approximate Relative Sizes of Vortex Atoms.—The approximate relative sizes in arbitary units of some of the most important elements, as calculated by the author on the basis of the foregoing electron vortex theory and a further theory which introduces the known atomic volumes, are set out in the following table, and in Fig. 10.

It is unavoidable that the details of the method employed must be omitted, as they are too involved to describe here.

Element.	Atom. Wt.	Mean Diameter.	Sectional Diameter.	Vortex Ratio.
		D.	d.	D/d.
H .	1·008	34·9	17·8	1·97
He .	3·99	36·2	22·8	1·6
C .	12	306·9	80·3	3·85
N .	14·01	176·6	62·4	2·83
O .	16	103·5	48·9	2·13
Al .	27·1	673·2	133·8	5·08
Si .	28·3	501·8	118·8	4·3
Ca .	40·09	2388·3	272·7	8·77
Fe .	55·85	622	148	4·27
Cu .	63·57	320	108·3	2·98
Ag .	107 88	569·2	126·7	2·92
W .	184·0	950	223·5	4·33
Pt .	195·2	357·8	137·2	2·6
Hg .	200·0	232·4	111·8	2·10



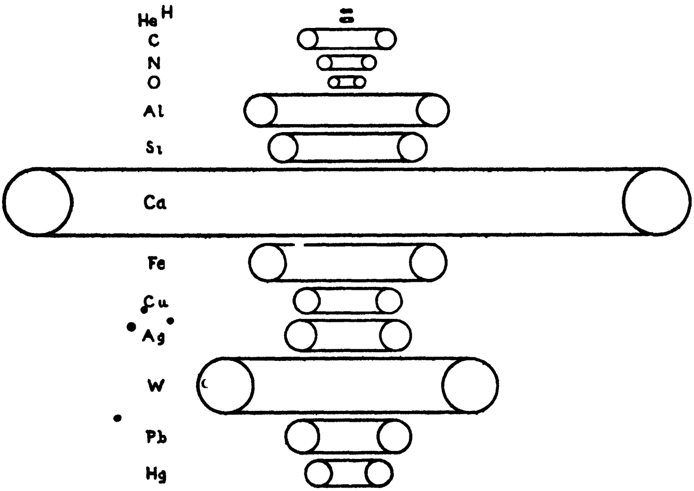


FIG. 10.—The Relative Sizes of some Atoms.

Speaking generally, the atoms of different elements which have the same "vortex ratio," that is, the same ratio of mean diameter to sectional diameter, react chemically in a similar manner.

CHAPTER II

ON PHASE DISPLACEMENT EFFECTS IN ELEMENTARY CIRCUITS

The Ether, and the Magnetic Field.—The Current along a Conductor, The Magnetic Field which accompanies it, and the Generation of Back E.M.F.—The Advantage of a Solenoid.—The Magnetic Fields due to Straight, Bent and Re-entrant Solenoids.—The Effect of adding an Iron Core.—The Phase Relationship of the E.M.F. required to drive a Current through a Circuit containing Resistance, Inductance, —both Resistance and Inductance.—The Electrostatic Field of a Condenser,—its Back E.M.F.—the Effect of a Direct Current Charge, and Independent Discharge.—A Condenser charged by an Alternating E.M.F.—the Phase Displacement due to Resistance in the Condenser Circuit.—A Circuit containing Capacity and Inductance subjected to a Short Application of a Steady E.M.F.—An Oscillatory Charge and Discharge following a Short Application of a Steady E.M.F. —Electromagnetic Radiation — The Conditions for Resonance in an Alternating Current Circuit.—The Effect on an Alternator of a Difference of Phase between the Current through its Windings and the Generated E.M.F. — The Limiting Power of an Alternator.—The Use of a Transformer to charge a Transmitting Condenser.—The Transformation Ratio — Phase Relationships in a Transformer. — The Magnitude Relationships of Current, E.M.F., Resistance, Inductance, and Capacity, in the Transformer Primary and Secondary Circuits.—Vector Quantities, and Vector Diagrams.—Current, and Potential Vectors. — Transformer Vector Diagrams for "No Load," "Non-Inductive Load," and "Capacity Load."—The Phase Effects of Magnetic Leakage.

IN this section we propose to study the "time" or "phase" relation between the E.M.F. applied to a circuit and the resulting current.

An electric current in a solid conductor consists, as we have said, in the motion of a stream of electrons or negative charges.

Each of these charges carries with it an electrostatic field, which, when it moves, produces a shear or twist in the surrounding ether. This twist shows itself as the magnetic field. When the charge or its electrostatic field comes to rest, the ether recovers from the shear and the magnetic field disappears. The action which takes place may be illustrated by the following model.

Imagine the ether to consist of a medium composed of elastic particles which can change their shape but not their volume, and which are tightly packed together under a constant pressure, as shown in section, Fig. 11 (*a*).[1] Let this section be subjected to an electrostatic strain indicated by the vertical lines, which are supposed to be normal to it. If this strain is not relieved, the section of the medium remains unaltered. But if there are negative charges present which can be put in motion by the applied E.M.F., then they will travel along the path set out by the lines of force, passing between the ether atoms, and exerting a pressure on them which will be greatest along lines radial to the centre of disturbance. This will cause the atoms to rearrange themselves, so that they occupy

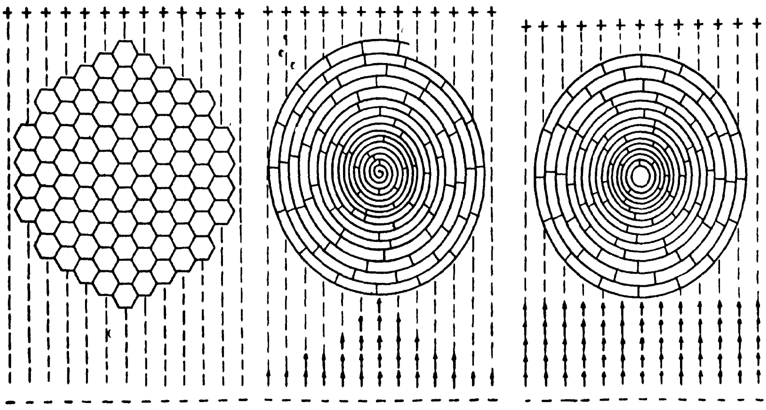

(*a*) (*b*) (*c*)

FIG. 11.—Model illustrating the Generation of a Magnetic Field.

---

[1] The number of ether corpuscles in (*a*), and (*b*), and (*c*) is supposed to be the same, and the cross-sectional area the same. This is not quite the case in these figures.

the same volume as before, but their dimensions on these radial lines will be less, and transverse to these lines will be greater, than the normal. They will form up in concentric layers, the thinness of the layers being in proportion to the speed and number of the moving charges. As the ether atoms in section will become longer and narrower, there will be rotation, or a spiral movement as they readjust themselves, each layer slipping over the next, Fig. 11 (*b*), until the equilibrium state is obtained, when the spiral collapses into a number of concentric rings, Fig. 11 (*c*), and remains thus until the pressure is altered, either by a further increase or a decrease. Hence the effect of shear or twist which is produced.

As the sense of the shear relative to the direction of movement of the charge is always the same, clockwise when the charge moves away from the observer, anti-clockwise when it approaches him, the method of progression of the charge and therefore of the shrinking lines of force is possibly also spiral. When the charges come to rest, although the electrostatic field may be maintained, the shearing force on the ether has been removed and it reverts to its original homogeneous state.

Let us consider what happens when a few of these charges move along a simple straight conductor under the influence of an applied E.M.F. The charges may be in local rotation before the E.M.F. is applied, but as they have no movement along the length of the conductor they are relatively "at rest." In starting up from "rest" as so defined, a magnetic field is generated at right angles to their direction of motion, which grows in intensity and reaches a maximum when the number and velocity of the charges reaches a maximum, and spreads outwards into space at the speed of light.

While the magnetic field is increasing in intensity, a Potential Difference is generated in the ether-filled space affected by it, which is a measure of the force with which the medium opposes the growth of the shear, and if a conductor is linked with the field or cut by it, this force becomes apparent as an E.M.F. which causes a current to flow along the conductor in a direction which opposes the increase; the reaction, in fact, being such as will tend to restore the disturbed equilibrium of the ether. The conductor carrying the moving charges which generate this magnetic field is equally subject to induction, as in the space it occupies the ether disturbance is a maximum. The value of the induced E.M.F. is proportional to the rate of change of the magnetic field, and therefore sinks to zero when the magnetic field ceases to change on reaching its maximum strength, which is another state of equilibrium for the ether.

The magnetic field flows, or the ether shear is transmitted, from a position of high intensity to one of low, so that when the number of charges which pass a certain point in the conductor become less, and their accompanying magnetic field is weaker than the field already impressed on the ether, the existing field then flows back towards the exciting conductor. This causes the field in the immediate neighbourhood of the conductor to become greater than that generated by the current and gives rise to an E.M.F. tending to maintain the current in the conductor at its old value. Also, any other conductor placed in the falling field will have a *rising* E.M.F. induced in it, parallel to, and in the same sense as, the exciting current. Finally, if we can imagine the charges proceeding an infinite distance up the conductor, the intensity of the magnetic field in the plane considered, the E.M.F. which can be induced by the magnetic field will once more reach zero, as all the energy impressed on this section of the ether will have been returned to the conductor.

The three stages are illustrated in Fig. 12, in which the thick barbed arrows represent the charges in the conductor, the circles the magnetic field, and the thin arrows the space P.D.'s, or their equivalent induced E.M.F.'s. At (*a*), where the current is a maximum, there is no back E.M.F., but the outflow of the magnetic field and its intensity reach a maximum.

At (*b*) the current strength has diminished, there is an inflow of magnetic energy back to the conductor as an assisting E.M.F.; while at (*c*), where the magnetic field is growing, there is an opposing E.M.F.

The arrows on the magnetic field indicate direction of shear, and not rotation, as it is evident that when the shear is growing the rotation will be in the same direction as the shear, but when the shear is disappearing the rotation will be in the opposite direction to the shear.

The example just given is that of a variable *direct* current. If there is a long middle period of constant current, then, although the outer limit of the magnetic field, if it could be observed, will still show a flow outwards, at any given point near the conductor the field will be maintained at the same intensity, and therefore will not induce an E.M.F. in any stationary conductor.

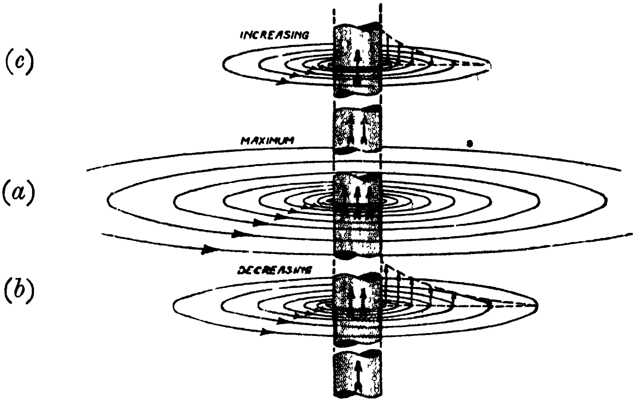


FIG. 12.—The Relation between the Current in a Conductor and the Magnetic Field and Back E.M.F. in the Surrounding Space.

Suppose that instead of only a few charges we have to deal with a great number, which are subjected to an impressed E.M.F. in the conductor, varying in sense very slowly, but continuously. Then the speed and direction of the flow of the charges will also vary in a corresponding manner. When the charges flow *down* the conductor instead of up as a result of a change in the sense of the applied E.M.F., the medium receives a twist in the *opposite* direction, the magnetic field is reversed, and changes in its intensity are accompanied by increases and decreases in the opposite sense of the E.M.F. it is able to induce in a conductor. There will be a cyclic variation then of the magnetic field accompanied by a cyclic variation of induced E.M.F. Providing there are no other absorbing circuits to consider, all the energy which leaves the conductor each cycle as magnetic field is returned to it later as induced E.M.F., so that there is no permanent loss to the conductor.

These are the characteristics of an *alternating* current. If the alternating current has a frequency of 50 cycles per second, the magnetic field will have travelled 930 miles within the interval of one quarter cycle from minimum to maximum current, and therefore before the field nearest to the conductor commences to flow back into it, so that supposing low frequency induction effects due to one exciting circuit are experienced in several simple conductors, which might be miles from each other and the exciting circuit, the induced E.M.F.'s may be different in quantity, but they will all have practically the same time, or phase relationship.

On the basis that the inductive effect of the magnetic field depends on the amount of linkage or coupling of the field with the conductor, a straight wire must be much less inductive than any form of coiled wire, and in this case, except at very high frequencies, the back E.M.F. is negligible. A straight wire is therefore often said to be non-inductive, but this condition is more nearly obtained if the wire is bent into a circle of one turn, and still more so if it is zigzagged or bent back on itself as a narrow loop, when the fields due to the parallel parts neutralise each other.

By giving the conductor the form of a solenoid (Fig. 13), the part of the field enclosed by it is linked many times with the circuit, and in consequence the self-induction effect is very pronounced.

What takes place is illustrated in Fig. 14. Every part of a turn generates its own section of magnetic field, the sections in the same plane join up and add their effects where the lines of force assist each other—that is, inside and outside the solenoid,—but between the turns where they oppose they represent twists in the ether in opposite directions and so balance out.

The compound field thus formed expands outwards into space, and also inwards towards the solenoid axis.

But the field from any one inside part of the solenoid is met by the fields of equal strength expanding inwards from all other inside parts of the solenoid. Further expansion is thus stopped, and the total field strength, or shear of the ether along the length of the solenoid, then averages out over the whole cross-section up to the mean area of the turns. When the current through the solenoid conductor falls, it generates a weaker field, and the stronger field already existing flows back into the turns and thereby generates an E.M.F. proportional to the difference in the two fields, which tends to delay the fall of the current.

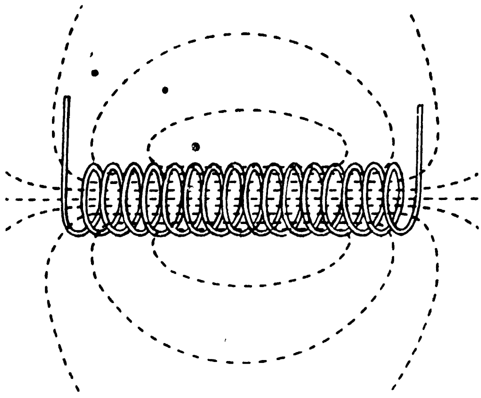


FIG. 13.—The Magnetic Field of a Solenoid.

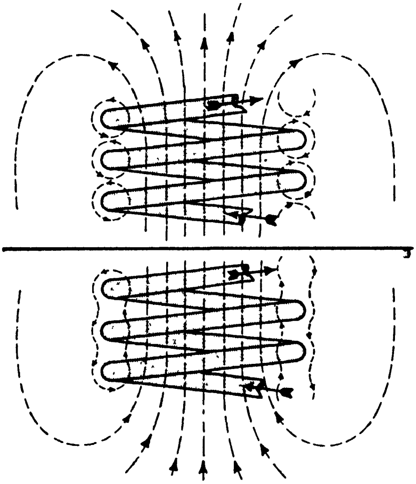


FIG. 14.—The Linking of the Lines due to each Turn in the Solenoid.

The magnetic lines of force always try to shorten themselves, as far as this can be done consistent with the repulsion, which exists between them. In other words, the medium resists shear and therefore tends to localise it.

Thus if the axis of the solenoid is slightly bent as shown in Fig. 15 (*a*), the greater part of the external field, which is not tied to the individual turns but to the solenoid as a whole, is now generated on its concave side, so that a conductor must be placed on this side to experience greatest inductive effect; and finally, if the inductive circuit is made a closed spiral (Fig. 15 (*b*)), all the linked field becomes totally enclosed, and there will be no external inductive effect. But it should be noted that although the intensity of the external field for the same solenoid alters in different directions with the curve of its axis, the strength of the internal field away from the ends is the same whether the axis is straight, or bent into a circle.

If there are N turns of wire per unit length of axis of the solenoid which has a sectional area A, and a magnetising current I, then H, the magnetic force in lines per square centimetre, is in each case $4\pi NI$; and F, the total field strength, is $4\pi NAI$. The self-induced E.M.F. which results from a change of field is therefore the same in each case. This means that the length of the path taken by the magnetic lines of force is only of importance as regards the distribution of the ether strain, it does not introduce any term equivalent to conductor resistance, the strength of the field depending solely on the dimensions of the solenoid.

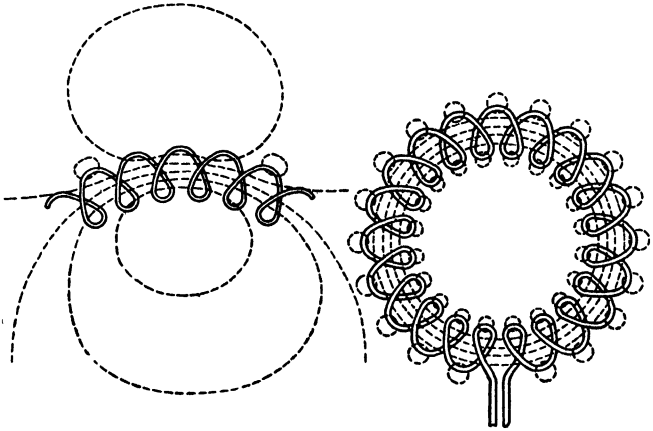

(*a*) (*b*)

Fig. 15.—The Magnetic Fields of Bent and Re-entrant Solenoids.

If the core of the solenoid is now filled with a continuous ring of iron the magnetisation will be very much increased. The magnetic force will become $\mu H = B$, the relation between the field strength in air and in iron being shown by the HB and $H\mu$ curves, Fig. 16. But in this case the field strength is very much greater than what would be obtained if the same solenoid were to be opened out so that its axis was straight, owing to the demagnetising action of the free ends of the iron core, and it has been found useful for purposes of calculation to introduce the term "reluctance," expressed by $r_m = \frac{l}{A\mu}$, as the equivalent resistance of the magnetic path when it contains iron.

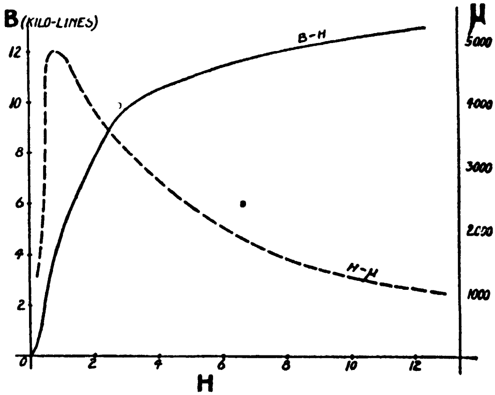


Fig. 16.—The Effect of Iron in a Solenoid.

The E.M.F. which it is necessary to apply to a circuit in order to cause a current to flow in it must clearly depend on the forces which have to be overcome in that circuit. There is first of all the opposition of the atoms of the metal to the passage through them of the travelling charges, or current I, which is covered by the term "Resistance," and denoted by R. The force which has to be overcome in the conductor is given by the product I × R; it synchronises exactly with the current, commencing the instant that the current starts, and ending the moment it stops. The E.M.F. required to overcome this force will therefore be opposite in direction, equal in amount, and synchronous with the current, and is denoted by V_R. The energy of the E.M.F. which is employed in overcoming resistance does not result in any elastic reaction in the circuit as with inductive, or capacitative, or electrolytic effects, it completely disappears from the circuit in the form of heat. But when the current alters its strength we have shown that, in addition to the forces of "Resistance," the opposing forces of "Induction" have also to be overcome by the applied E.M.F. and these are not synchronous with the current.

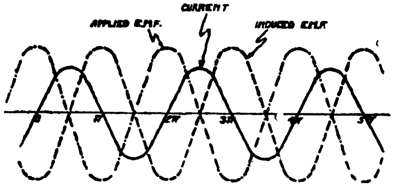


FIG. 17.—Alternating Current and Potential Curves for a Circuit containing Inductance only.

As the current falls, the induced E.M.F. commences to rise on the same side of zero, Fig. 17. This is equivalent to the current having completed one quarter cycle of alternation before the induced E.M.F. has started its period, or to a *lead* on the induced E.M.F. of 90°.

As the applied E.M.F. must be equal in amount, and opposite in phase or direction to the induced E.M.F., the current therefore *lags behind* the applied E.M.F. by 90°. In this case the resistance of the circuit is supposed to be negligible, so that the V_R curve required to overcome resistance is not shown.

As already pointed out, the growth of the magnetic field is synchronous, or in phase, with the current; but the assumed rotation of the ether causing the shear will be in phase with the applied E.M.F.

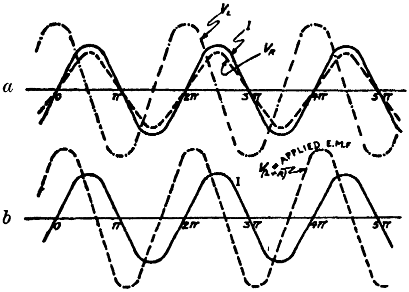


FIG. 18.—Alternating Current and Potential Curves for a Circuit containing Inductance and Resistance.

Suppose we have to apply an E.M.F. to overcome both resistance and induction effects in a circuit. The separate E.M.F.'s required are shown by the curves V_R and V_L, Fig. 18 (*a*). Then if the ordinates which give these two curves are added together, we get the curve $(V_R + V_L)$, Fig. 18 (*b*), from which it will be seen that the current now lags behind the applied E.M.F. less than 90°.

Thus the effect of resistance in an inductive circuit is to decrease the angle of lag of the current relative to the applied E.M.F.

When an E.M.F. is applied to a circuit containing a condenser, negative charges are torn from the dielectric and stream along the conductor from the condenser on the one side, which is thus made positive, and towards it on the other, which therefore becomes negative.

Arriving at the condenser the charges can go no further. They pile up on the surface of the dielectric and are held there by the applied E.M.F., which acts against their own electrostatic forces urging them back to the atoms from which they have been torn, Fig. 19.

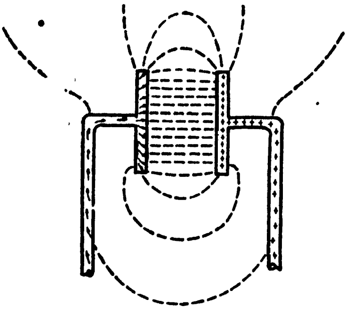


FIG. 19.—The Electrostatic Field of a Condenser.

The lines of force of the electrostatic field which is thereby set up take all paths between their terminal charges, direct through the dielectric to the positive side of the condenser, and between the conductors connected to the plates of the condenser, thereby establishing a static P.D.; and in addition, while the current is still flowing, this P.D. will show itself in the conductors as a back E.M.F.

It is clear that the greater the number of charges which are thus piled up, the greater must be the field through the condenser and its equivalent, the back E.M.F. in the conducting circuit, which, as it grows, reduces the charging current, and on reaching the value of the applied E.M.F., stops the current altogether.

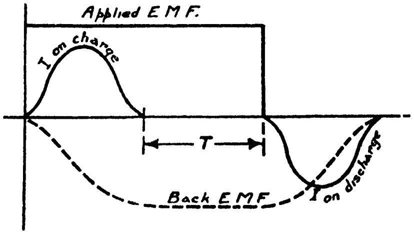


FIG. 20.—The Current and Potential Curves of a Condenser charged by a Steady E.M.F. and then discharged.

The rise and fall of the charging current and the rise of the back E.M.F. under the influence of a constant applied E.M.F. are shown in Fig. 20. If after an interval T, the applied E.M.F. is removed, the back E.M.F. causes a current to flow in the opposite direction through the circuit, thus discharging the condenser. The current first rises, reaches a maximum, and then falls, while the back E.M.F. steadily falls, and both reach zero when the condenser is completely discharged.

Suppose the condenser circuit is now subjected to an alternating current. If its resistance can be neglected, the only force to be overcome in the circuit is that of the back E.M.F. This must continue to rise as long as there is any current flowing and therefore any charges to pile up on the condenser. On reversal of the current the charges will return to the circuit and the back E.M.F. will fall. When the reverse current reaches its maximum, all the charge will have left the condenser and be in the conductor, and the back E.M.F. will have fallen to zero.

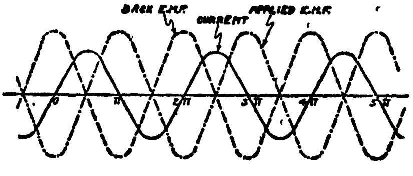


Fig. 21.—The Current and Potential Curves of a Condenser Circuit charged by an Alternating E.M.F.

As the applied E.M.F. must be opposite in phase and equal in magnitude to the back E.M.F., we therefore get E.M.F. and current curves as shown in Fig. 21. The current is just commencing to fall as the applied E.M.F. is beginning to rise; it is therefore said to *lead* the applied E.M.F. by 90°.

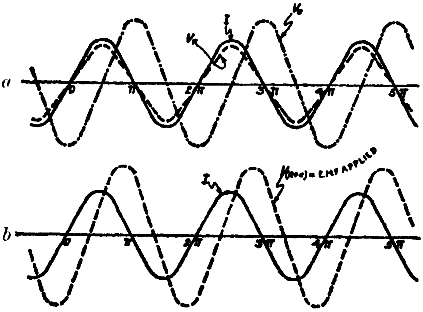


Fig. 22.—The Current and Potential Curves of a Condenser Circuit containing Resistance, charged by an Alternating E.M.F.

If the E.M.F. is now added which is required to overcome ohmic resistance in the conductor, which must be in phase with the current and proportional to it, as shown by the curve V_r, Fig. 22 (*a*), the compound curve V_{r+k}, Fig. 22 (*b*), is obtained, from which it will be seen that the effect of resistance in a circuit containing capacity is to reduce the "lead" of the current on the applied E.M.F.

If we have a circuit which contains inductance, capacity, and resistance, and a D.C. E.M.F. is applied to it (Fig. 23), as the current rises energy is first stored in both the inductance and capacity, and dissipated in the resistance ; when the current falls as a result of the steady increase of back E.M.F. exerted by the accumulating charge in the condenser, the energy in the inductance is given back into the circuit and used to complete the charging of the condenser, while the resistance continues to absorb energy until the current ceases.

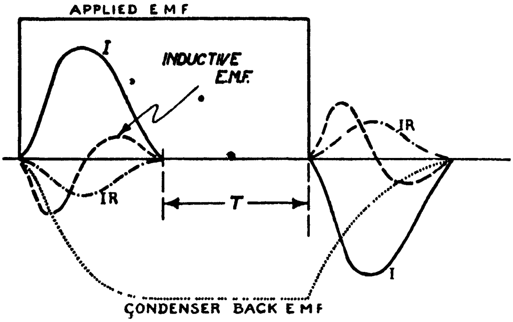


FIG. 23.—The Charge and Discharge Curves of a Circuit containing both Inductance and Capacity, and excited by a Steady E.M.F.

If, after an interval T, the external E.M.F. is removed, the back E.M.F. of the condenser starts a current in the reverse direction through the circuit accompanied by an alternation of induced E.M.F., which first takes energy from the current and then returns it, while the resistance absorbs energy until the current ceases.

This is the simple case where R produces a dead-beat current. But if R is less than $\sqrt{\frac{4L}{C}}$ the current rise is greater, the condenser discharges quicker, and more energy is released in the circuit than can be immediately used up by the resistance. It becomes stored in the inductance, which later on returns it to the circuit as the current falls, with the result that the current does not end when it reaches the zero line, but reverses and recharges the condenser in the opposite direction, and there results a series of surges of current and potential until the whole of the energy is finally dissipated (see the right-hand part of Fig. 24). Here we come in touch with the phenomena of *oscillatory* currents, in which the energy of the circuit changes its character at regular intervals from potential to kinetic and kinetic to potential, like the energy of a swinging pendulum, until it has all been absorbed by the circuit resistance.

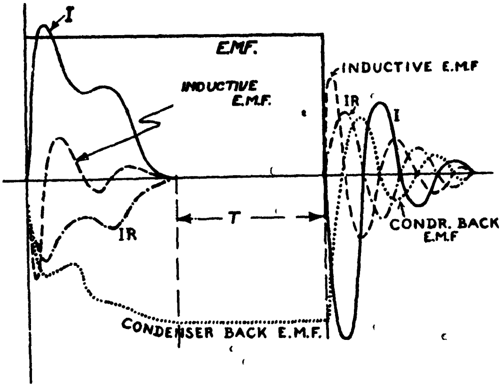


FIG. 24.—An Oscillatory Charge and Discharge.

A condenser charged by direct current through an inductive circuit of low resistance experiences similar ripple effects, as is shown in the left-hand part of Fig. 24.

Now when a circuit is set in electrical oscillation in this way it vibrates at its *natural period*, and the frequency of the oscillations "*n*" can be calculated from the known values of L, C, and R. If R is negligible,

$$n_{\text{per sec.}} = \frac{1}{2\pi\sqrt{L_{\text{hry.}}\, C_{\text{farads}}}}.$$

The natural period of any circuit is such that the time taken to store a given amount of energy in its magnetic field is the same as that required to store the same amount of energy in its electrostatic field. At any instant the energy given up by the condenser is being conserved by the magnetic field and dissipated by the resistance, and at the instant the magnetic field commences to give up its energy, the condenser commences to absorb it.

An oscillatory current can be started by interrupting the charging current of a condenser so suddenly that the E.M.F. induced in the conductor by the rapid change in the magnetic field is sufficient to cause a spark to jump the gap at the point of interruption, A, Fig. 25. The almost complete disappearance of the gap resistance releases the pent-up energy of the condenser, which, if more than the circuit can immediately absorb, starts a current surge backwards and forwards through the gap at the natural frequency of the circuit. Instead of suddenly interrupting the charging current, the potential of the condenser can be increased until it reaches the critical value of the gap A, when breakdown occurs with accompanying surges of current as already described. As the current rises the condenser potential falls; as the current falls the condenser potential rises.

The current creates a magnetic field in space, the charge in the condenser creates an electrostatic field in space, and the two fields permeate each other in planes at right angles.

If the charges come to rest, the electrostatic field reaches a steady state, and the magnetic field dies out. But if the charges move in such a way as, to make the electrostatic lines of force cross each other, the lines join up and break off in closed loops, and travel into space linked with the expanding magnetic field, which as long as it is so linked does not die out. This is *electromagnetic radiation.*

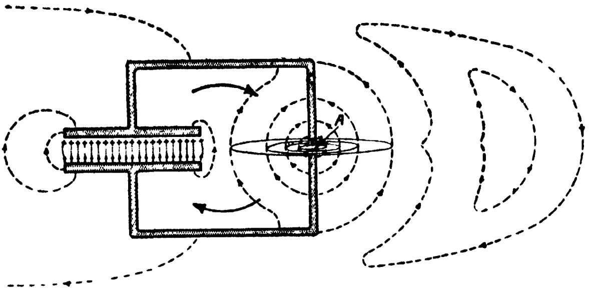


FIG. 25.—Electromagnetic Radiation from an Oscillatory Circuit.

The point of greatest current in the oscillatory circuit, and therefore strongest magnetic field, is midway along the inductance of the conductor, and this is also the position of zero potential. Towards the condenser, either way, the potential grows and wanes, alternately positive or negative.

When, during a surge, the potential of the condenser commences to rise, electrostatic lines of force generate at this point and expand into space, while their ends travel to the condenser along the conductor and normal to its surface.

When the potential falls these lines collapse again to the position from which they started, but portions of them never return, owing to the formation and separation of the closed loops as the charge reverses in the condenser.

Whereas in the oscillatory circuit itself, the potential causing a surge leads the current by 90°, and the electrostatic field in space which is attached to the circuit must therefore also be 90° out of phase with the magnetic field, the detached loops of electrostatic strain almost immediately settle down to an "in phase" relationship with the magnetic field.

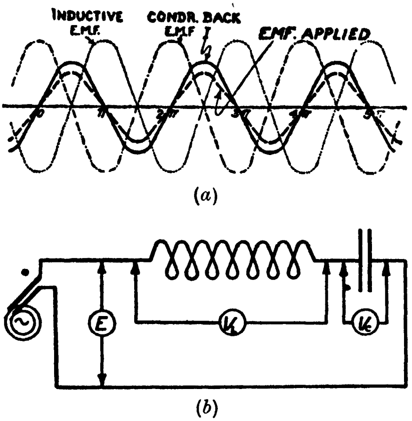
Let us now study the results which follow from the application of a simple alternating current to a circuit containing inductance, capacity, and resistance.

It is clear that if inductance causes the current to lag, and capacity causes the current to lead, then it should be possible to find such values of inductance and capacity that the two effects balance, and the current remains in phase with the impressed E.M.F.

This condition is reached when the amplitude of the back E.M.F. due to the inductance is equal to that due to capacity, Fig. 26 (*a*), the potential measurements V_L and V_c being made as shown in Fig. 26 (*b*). The only E.M.F. which must then be applied to the circuit to drive a current through it is that required to overcome its ohmic resistance, which is in phase with the current. If the wave form of the applied E.M.F. is sinoidal and the resistance of the circuit is comparatively small, then the back E.M.F. due to the condenser is given by $V_c = \frac{I}{2\pi nC}$, and the induced E.M.F. due to the inductance by

$V_L = 2\pi nLI$,

so that if $V_c = V_L$, $\frac{I}{2\pi nC} = 2\pi nLI$ and $n = \frac{1}{2\pi\sqrt{LC}}$,



(*a*)

(*b*)

FIG. 26.—The Conditions for Resonance in an Alternating Current Circuit.

which is the expression for the natural frequency of the circuit. This is the condition of *Resonance*, which is obtained when the applied frequency is the same as the natural frequency, and which requires a minimum terminal E.M.F., measured across both inductance and capacity (Fig. 26 (*b*)), to produce a given value of alternating current, or, if the terminal E.M.F. is fixed, produces a maximum current.

And it follows that if the terminal E.M.F. is kept constant, the current being a maximum, the potential drop, measured across either the inductance or capacity which depends on the current, will also be a maximum.

It is useful to note here the effect on the supply from the alternator of a difference of phase between the current through its armature windings and the induced E.M.F. The induced E.M.F. corresponds to the terminal voltage on open circuit, but not to the terminal voltage on load, which then has a phase relation with the current determined by the armature impedance. If the total lagging effect of inductance in the circuit as a whole is not balanced by the total leading effect of capacity, the current through the armature will either lag behind, or lead the induced E.M.F.

The drop in terminal voltage between no load and full load is determined (1) by dead losses, due to the ohmic resistance of the winding, and eddy currents induced by the varying armature flux; (2) the inductance of the armature winding; (3) the phase of the armature current.

A lagging current increases the armature demagnetising ampere-turns, so that the main field is weakened and the induced E.M.F. is lowered. A leading current reduces the demagnetising ampere-turns and therefore tends to increase the induced E.M.F.

The maximum output of an alternator is determined by its induced E.M.F., and its reactance, which is principally inductance. The limiting or short circuit current of the machine will be that current which will produce a back E.M.F. equal to the induced E.M.F.

Then for a given E.M.F., the larger the inductance of the alternator winding the bigger the drop on load, the smaller the limiting current, and the less the maximum output.

If E = induced E.M.F.,
L = effective alternator inductance on full load,
I = short circuit current,
x = some constant,

then a rough rule for the limiting power in watts, W, of an alternator on non-inductive load is given by

$$W = xEI = xE \times \frac{E}{2\pi nL} = x\frac{E^2}{2\pi nL},$$

and for usual work $W = \frac{E^2}{20nL}$.

It can be shown also that this formula covers the case of an alternator working on a circuit in resonance with the alternator frequency.

The condenser in the radio transmitting circuit is not usually connected to the generator in the direct manner shown in Fig. 26 (*b*), but through a transformer (Fig. 27), which provides a simple means of raising the supply voltage to the charging potential required to give the necessary power to the H.F. discharge circuit. If we take the ring solenoid with its continuous iron core discussed on p. 24, we can make a transformer of it by winding on a second solenoid over the first.

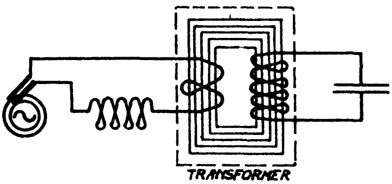


FIG. 27.—The Transmitting Condenser connected in Circuit through a Transformer.

Then any change in the magnetic state of the iron produced by a varying current in the first coil, the "primary," will induce an E.M.F. in this coil as well as in the second coil, the "secondary," which will be proportional in each case to the number of turns of the respective coils.

If the resistance of the primary can be neglected, and all the lines generated by the primary pass through the secondary, the ratio of the induced E.M.F. of the secondary to the E.M.F. impressed on the primary for the purpose of overcoming its back E.M.F. will be

$$\frac{E_s}{E_p} = \frac{N_s}{N_p} = T,$$

where T is the *transformation ratio.*

If the resistance of the primary can be neglected, the magnetic field will be synchronous with the primary current, and the E.M.F.'s induced by the variations of the field will lag 90° behind the primary current.

If the secondary is open-circuited so that only the back E.M.F. in the primary has to be considered, the transformer behaves like a simple inductance coil; but if a current is taken from the secondary, the magnetic field associated with it introduces a new set of reactions.

A non-inductive load on the secondary will have the current through it in phase with the terminal voltage, but the same current will lag 90° behind the induced E.M.F. in the winding and therefore 180° behind the primary current. Its field will therefore be in opposition to the field produced by the primary, so that the total magnetic induction will fall. But immediately it falls, the back E.M.F. in the primary falls, and if the applied terminal potential is maintained, the current rises and new flux is produced as fast as the old flux is used up as current in the secondary winding. Thus the transformer within its working range is self-regulating. Since the back E.M.F. remains constant while the current experiences a considerable increase, the effective primary inductance of the transformer correspondingly falls, and the current gets more in phase with the applied E.M.F.

The current through the primary winding therefore produces a constant magnetisation of the core from no load to full load, and also provides the magnetic flux necessary to meet the opposing flux of the secondary circuit.

As in modern transformers the magnetising current is only a very small fraction of the full load current, the primary ampere-turns at full load therefore practically equal the secondary ampere-turns.

$$I_s N_s = I_p N_p, \text{ then } \frac{I_s}{I_p} = \frac{N_p}{N_s} = \frac{1}{T}.$$

Or, the ratio of the secondary current to the primary current is inversely proportional to the transformation ratio.

Now as all secondary circuit E.M.F.'s and currents are dependent on the main E.M.F. and current induced in the transformer secondary winding, equivalent values in the primary circuit can be found for them by using the transformation ratio as it is applied to this winding. Thus a non-inductive resistance across the secondary circuit can be measured by the ratio of the terminal potential V_s to the current I_s.

$$R_s = \frac{V_s}{I_s}, \text{ and therefore } \frac{R_s}{R_p} = \frac{V_s \times I_p}{V_p \times I_s} = T \times T = T^2, \text{ and } R_p = \frac{R_s}{T^2}.$$

Or, a secondary resistance must be divided by the square of the transformation ratio to give the equivalent primary resistance.

Again, a secondary inductance can be measured by taking the drop in volts across it, and the current through it,

$$\text{then } L = \frac{V_{ls}}{2\pi n I_s} = \frac{1}{2\pi n} \times \frac{V_{ls}}{I_s}.$$

The two variables V_{ls} and I_s have a similar relation in the measurement of resistance, and the equivalent value of inductance in the primary circuit can therefore be found by applying the transformation ratio as for resistance—

$$L_p = \frac{L_s}{T^2}.$$

A capacity C_s, however, has an inverse relation to a resistance, thus

$$C_s = \frac{I_s}{2\pi n V_{cs}},$$

and therefore a capacity in the secondary circuit requires to be multiplied by the square of the transformation ratio to find its equivalent in the primary circuit,

$$C_p = C_s T^2.$$

Then it is clear that a condenser which is connected to the main circuit through a transformer is still able to cause a leading current in the main circuit.

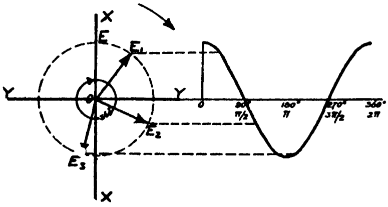
The effective back E.M.F. in the main circuit measured at the terminals of the transformer primary will be given by the expression

$$V_{cp} = \frac{I_p}{2\pi n C_s T^2} - 2\pi n L_{tp} I_p,$$

where L_{tp} is the effective leakage inductance of the transformer, which, in a properly constructed machine having a closed iron core, is usually negligible.

If the current is leading, the transformer terminal potential will be greater than the terminal potential measured across the circuit inductance external to the alternator, plus the potential drop which must be allowed for the inductance in the alternator.

Vector Diagrams.—Alternating current problems involve *vector quantities,* that is, quantities which are only completely specified when their magnitudes are given with reference to their time or phase, and direction or sense, relationships; and their actions can be studied most conveniently, therefore, by the use of *vectors*—lines which, by their length, inclination, and direction, represent such vector quantities. As a first illustration consider the variation during one complete period of a single vector quantity such as E.M.F. Draw a vertical line XX (Fig. 28 (*a*)), and from its middle point O mark off a distance OE representing the E.M.F. vector (maximum value) of an A.C. circuit.



(*a*) (*b*)

FIG. 28.—An explanatory Vector Diagram.

Then the revolution of OE about O, returning to its original position on XX, will represent one complete alternation or cycle of 360 electrical degrees, or of 2 π radians.

In order that the E.M.F. vector may be correctly shown in having its maximum value OE on XX, as the E.M.F. only reaches its maximum value after one quarter cycle, that is, at a phase position of 90°, the phase position of OE must be measured relative to an axis YY at right angles to XX. Let OE revolve about O in a clockwise direction taking up the successive positions OE_1, OE_2, OE_3, etc. Then the projections of the rotating vector on XX will give its instantaneous values, positive or negative, at the phase positions measured relative to YY, and these are plotted in the usual manner (Fig. 28 (*b*)) with phase angles or time as abscissae and E.M.F. values as ordinates.

If we are concerned with more vector quantities than one, which all have the same frequency of alternation, and we wish to show the phase relations which exist between them, then it is sufficient to draw vectors representing their maximum or their R.M.S. values from a common centre O, and relative to a single axis YY.

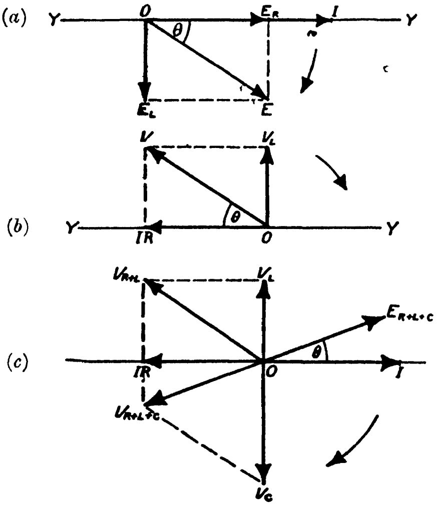


FIG. 29.—Vector Diagrams involving Inductance, Capacitance, and Resistance Quantities.

Thus in Fig. 29 (*a*), OI is the current vector and OE the vector of impressed E.M.F. which leads it by a phase angle θ. By dropping a perpendicular from E on to YY, OE can be resolved into a component OE_R in phase with the current, which is therefore the E.M.F. required to overcome the non-inductive resistance of the circuit, and another component EE_R, or OE_L leading the current by 90°, required to overcome the inductive reactance of the circuit.

The potential difference due to resistance, the induced potential, and their resultant, which the resultant impressed E.M.F., OE, is required to overcome, are shown by the vectors OIR, OV_L, and OV, in Fig. 29 (*b*), equal in magnitude but opposite in sense to the vectors OE_R, OE_L, and OE, in Fig. 29 (*a*).

If it be understood that all phase angles are measured relative to a horizontal line drawn right or left of O, as convenience may decide, we can make one of the vectors the line of reference in place of the axis YY.

Let it be required, for example, to find the difference in phase between the current and the impressed E.M.F. in a circuit containing resistance, inductance, and capacity.

Then proceed as in Fig. 29 (*c*), and from a centre O set off the current vector OI, which will be our axis of reference.

As the E.M.F. required to overcome resistance is in phase with and in the same direction as the current, the potential drop due to the resistance, IR, can be shown by the vector OIR in line with OI, but opposite in direction; the inductance reactance which lags 90° behind the current can be represented by the vector OV_L, and the capacity reactance which leads the current by 90° can be represented by the vector OV_C.

We have first to find the resultant of OIR, OV_L, and OV_C; then draw a vector equal in magnitude to it, but opposite in sense, to represent the impressed E.M.F., and finally to measure the phase angle between this vector and the current vector.

Complete the parallelogram OIR, V_{R+L}, V_L, and draw the diagonal OV_{R+L}. Then OV_{R+L} is the resultant of two of the vector quantities, namely, the resistance drop and inductance reactance. Next combine this resultant with the vector of capacity reactance by drawing the parallelogram O, V_{R+L}, V_{R+L+C}, V_C, and its diagonal OV_{R+L+C}. The E.M.F. which is required to overcome this final resultant P.D. is shown by the vector OE, equal in magnitude but opposite in sense to OV_{R+L+C}, which makes an angle of $\theta°$ lag with the current vector.

To avoid misunderstanding it must be emphasised that resistance is not a quality which keeps energy *in* the circuit; it acts as a valve only, and lets energy *out*. The 180° phase difference of the vector OIR, as shown above, has therefore no significance *in the circuit*, but it is of use in the diagram to obtain the resultant of all the forces which the applied E.M.F. is required to overcome.

Vector diagrams are particularly useful in giving a clear presentation of the current, flux, and voltage relationships which exist in transformer circuits. The diagram Fig. 30 gives conditions in a transformer at "no load."

Since the secondary is open-circuited, we have only to consider the conditions in the primary circuit.

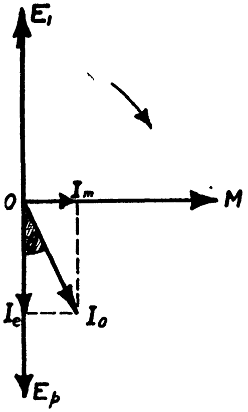


FIG. 30.—A Transformer "No Load" Vector Diagram.

The vector OM represents the core flux, and OI_m marked off along it represents the magnetising component of the current, which is in phase with the flux. Since the back E.M.F. induced in the primary lags 90° behind the flux, its magnitude and phase are given by the vector OE_1. If we neglect the E.M.F. which must be supplied to overcome resistance—which must, of course, be in phase with the resultant current—the pressure applied to the primary will be 180° in advance of OE_1, and therefore is represented by the vector OE_p. As the energy component of the current—that is, the part which is required to make good the hysteresis, eddy current, and resistance losses—must be in phase with E_p, it is shown as OI_e.

Completing the parallelogram O, I_m, I_0, I_e, and drawing its diagonal, gives us the resultant or main current vector OI_0, which lags θ°—in most cases about 50°—behind E_p, the E.M.F. applied at the terminals of the transformer.

In order to simplify the construction of the " load " diagram of a transformer it is usual to treat all the values, primary and secondary, as if they were in one circuit, the primary. The vectors of all the secondary values are therefore shown reduced to their primary circuit equivalents as found by the transformer ratio formulæ, pp. 34–37. This method does not introduce additional error, nor does it affect the relative phase angles which the vector diagram is principally required to show.

The " non-inductive " load diagram for a transformer which has no magnetic leakage—that is, one in which all the flux generated by the primary current cuts the secondary winding, and all the flux generated by the secondary current cuts the primary winding—is shown in Fig. 31. OM represents the core flux as before, and OE_1 the back E.M.F. in the primary in quadrature with it. Then OE_1, when multiplied by the transformation ratio T, will also give in magnitude and phase the back E.M.F. in the secondary. The no-load current I_0, involving the magnetising and energy components shown in Fig. 30, is represented by the vector OI_0. The load being non-inductive, the secondary current must be in phase with the secondary E.M.F., and is therefore shown by the vector OI_s superposed on OE_1.

Now the full-load primary current is the resultant of the no-load current I_0 and a component equivalent to, but opposite in sense to, the secondary current.

Then OI_{si}, equal in length to OI_s but leading it by 180°, will represent this second component, which, when compounded with OI_0, gives the primary current vector OI_p.

The magnitude and phase of the E.M.F. applied to the primary can be got by following up the construction a step further.

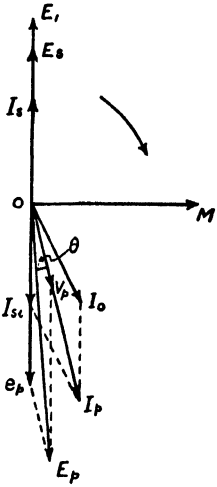


FIG. 31.—A Transformer "Non-Inductive Load" Vector Diagram.

This E.M.F. has two functions—(1) to balance the back E.M.F.; (2) to overcome the potential drop due to resistance.

The component which carries out the first operation is shown by the vector Oe_p, equal in magnitude but opposite in phase to OE_1; while the second component is OV_p, which is in phase with the primary current and therefore marked off along the vector OI_p.

Then the resultant vector OE_p, leading the current by the phase angle θ, represents the E.M.F. applied to the primary.

The terminal potential on the secondary at full load is represented by

$$OE_S = OE_1 - E_1E_S,$$

that is, by the induced E.M.F. minus the potential drop due to the resistance of the secondary winding.

A comparison of Fig. 30 with Fig. 31 shows that the change from no load to non-inductive load lessens the angle of lag between the applied E.M.F. and the current, and in practice this angle is so small that for most purposes the potential applied to the primary may be considered to be in phase with the primary current.

If the load on the secondary is inductive the secondary current lags, and its field is thereby rendered less effective in neutralising the field due to the primary current, with the result that the angle of lag between the applied E.M.F. and the current is increased.

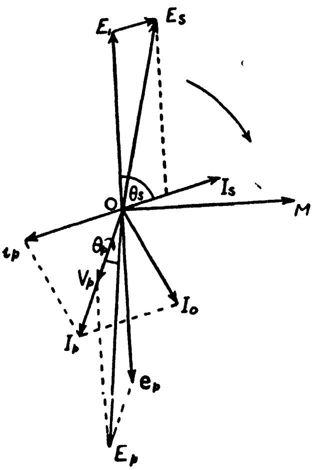


FIG. 32.—A Transformer "Capacity Load" Vector Diagram.

Thus an inductive load on the secondary has the effect of adding an equivalent inductive load to the primary.

The case of a "capacity load" on a transformer which is supposed to have no magnetic leakage is worked out in Fig. 32. The vectors of core flux OM, no-load current OI_0, back E.M.F. in primary or secondary OE_1, are drawn as in the non-inductive load diagram. But the secondary current OI_s, instead of being synchronous with the secondary E.M.F., now leads it by the phase angle θ_s.

The component of the primary current required to balance the secondary ampere-turns is Oi_p, drawn equal and opposite to OI_s. Compounded with OI_0 it gives the primary full-load current OI_p. To obtain the vector for the terminal E.M.F. impressed on the primary, draw Oe_p, equal and opposite to OE_1 and therefore representing the vector of potential required to overcome the back E.M.F.; also mark off OV_p along OI_p, representing the ohmic potential drop in phase with the current. Then the resultant of $Oe_p + OV_p = OE_p$, the primary terminal E.M.F., and in this case it is seen that the primary current *leads* the terminal E.M.F. by the phase angle θ_p.

The secondary terminal E.M.F. can be got by compounding the induced E.M.F., represented by the vector OE_1, with E_1E_s, representing the secondary ohmic drop, which, as it is in phase with the secondary current, is drawn parallel to OI_s. We thus obtain the vector OE_s. Then the effect of a leading current in the secondary is to decrease the normal lag of the current in the primary. If the angle of lead in the secondary is large enough, it will also cause the primary current to lead, but to a less extent.

If the transformer has magnetic leakage (Fig. 33), the lines of force generated by either coil which do not thread through the other, produce an effect in the circuit of added series inductance, and the vector diagrams become more complicated. The general results of magnetic leakage are—(1) to increase the phase difference between the primary applied E.M.F. and the current; (2) to lower the transformation ratio on inductive load. On non-inductive load the ratio remains practically unaffected.

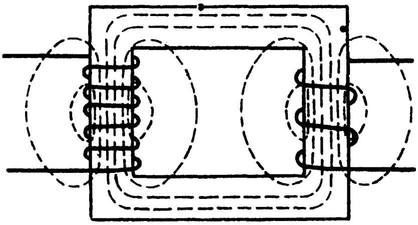


FIG. 33.—Magnetic Leakage in a Transformer.

CHAPTER III

THE SPARK DISCHARGE

A Common Method of starting an Oscillatory Current.—Amplification of Current and Condenser P.D. due to Resonance.—The Condenser Discharge Circuit.—The Timing of the Discharge,—The Factors which should determine it—The Paths open to the Discharge.—The Resistance of the Gap,—Discharge when the Main Current is falling.—The Condition of the Gases in the Spark-Gap.—Necessity for Metallic Vapour.—Relation of Gap Conductivity to Power in the Spark—Resonance in relation to Spark Discharge.—Resonance when Sparking,—Conditions required.—The Case for the Leading Charging Current,—And for the Lagging Charging Current.—The Lagging Effect of the Discharge,—The Phase at which the Spark Discharge should be taken, varies with the Conditions of each Circuit.—The most Efficient Type of Charging Circuit.—The Principle of the Marconi Disc Discharger.—The Scale of Spark Phase.—What it indicates—The Burning of the Electrodes by the Spark—The Use of Disc Electrodes.—The Effect of Windage.—The Arc at Break,—The Importance of the Time of Interruption of the Spark.—The Marconi-Mackie Disc Discharger.—The Calibration of the Disc Discharger for Spark Phase.—The Use of a Telephone,—Milliammeter—Transformer and Disc Discharger.—To adjust the Spark Phase.—The Best Audible Note.—The Plain Discharger.—The Use of Leading or Lagging Current—The "Quenched-Spark" Discharge.—Coupled Circuit Reactions.—The Effect of strongly damping the Oscillations in the Condenser Circuit.—Shock Excitation—The Telefunken Type of Gap.—The Marconi Type,—The Effect of de-tuning the Aerial Circuit—The Effect on the Tuning of increasing the Power applied to the Gap.

WE shall next consider the question of phase in relation to the spark discharge.

A very general way of starting an oscillatory current is to short-circuit a condenser charged by a low-frequency alternating current, through a path of low impedance and therefore of short time period.

The most efficient condition of the charging circuit, as already shown, is when it is in resonance with the supply frequency.

Fig. 34 shows the current, E.M.F., and condenser P.D. curves, for a circuit in which such conditions exist, and the consequent amplification as a result of resonance of the current and condenser P.D. which is only limited by the resistance of the circuit.

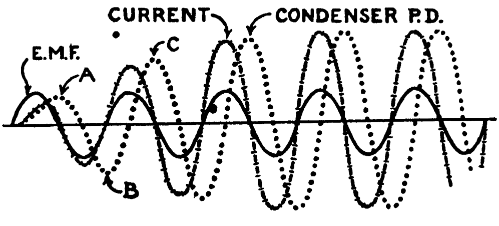


FIG. 34.—The Amplification of Current and Condenser P.D. due to Resonance.

Energy is stored alternately in the magnetic field and in the condenser. It remains in a surging state in the circuit but is not used up, so that the fresh energy which the alternator adds to the circuit each half cycle causes the current to increase, until it reaches such a value that the losses in the circuit due to resistance—which depend on the square of the current—increase sufficiently to equal the energy supplied by the alternator. The amplitude then reaches a maximum, and remains constant.

To the circuit shown in Fig. 27 we must add the path GCL (Fig. 35) for the condenser discharge, G representing an air-gap which is broken down by a spark when the voltage across it—and therefore the potential on the condenser—reaches a certain critical value.

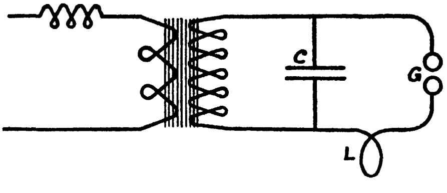


FIG. 35.—The Transmitting Condenser Charge and Discharge Circuits.

The part L of the circuit represents a coupling coil, or "jigger primary," which may be used for transferring the oscillatory energy to another circuit.

Now if the moment of discharge can be controlled, as is possible with the Marconi Disc Discharger—see p. 53,—it would seem advantageous to time the discharge so that it should take place at that instant when the alternating current has all been transformed into condenser charge, that is, just before the current commences to flow in the opposite direction which would allow the condenser to return its stored-up energy to the circuit.

Also, as the discharge establishes a temporary short circuit across the mains, it would appear advisable that the discharge should occur when there was no charging current flowing. That is, it should take place preferably at the moments A or B or C (Fig. 34), and if there are reasons why the discharge cannot, or should not, be taken at these phase positions, then it would seem better for the discharge to take place when the current is approaching zero and when, therefore, the short-circuit current through the spark-gap is a falling current, than when it has passed zero, and is rising.

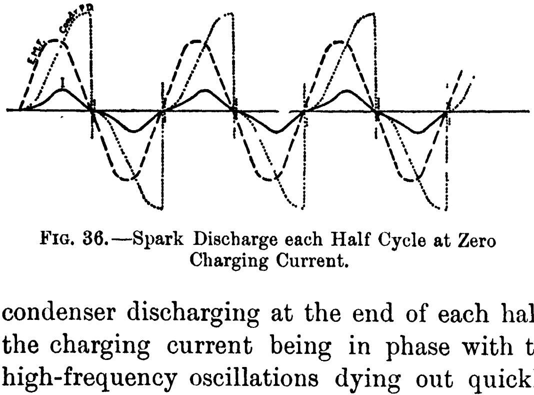


FIG. 36.—Spark Discharge each Half Cycle at Zero Charging Current.

Fig. 36 shows the condition usually illustrated, which represents the spark taking place and the condenser discharging at the end of each half cycle of current, the charging current being in phase with the E.M.F. and the high-frequency oscillations dying out quickly, due principally to resistance loss in the spark.

But the conditions of discharge are not so simple as this. There are several other determining factors which must be briefly referred to.

To begin with, the discharge from the condenser will have two paths open for it, the first, back along the charging circuit as a low-frequency current, and the second across the conducting air-gap as a high-frequency current. The discharge will divide between them in the inverse proportion to their respective reactances.

If the resistance of the gap has not been sufficiently lowered by the spark, quite a large proportion of the condenser charge may flow back into the main circuit.

Again, it has been shown (see Fig. 21) that the oscillatory discharge of a condenser results in the maximum current occurring at minimum voltage, so that at maximum current the voltage across the electrodes may fall to a value which is insufficient to maintain the conductivity of the spark, and the discharge will therefore cease. If the potential of the condenser charge which still remains is insufficient to break down the gap resistance, the charge will take the alternative path back into the mains as a low-frequency current. This quenching of the high-frequency discharge may occur after the first, second, or later alternations, depending on the rate of decay of the spark-train, and the rate of recovery of the air-gap insulation.

But suppose the discharge is set to occur when the main current is falling, but before it reaches zero value, then, as it takes a much lower voltage to maintain a conducting path through the air than to produce one, the small potential difference across the spark-gap resulting from this main current may be quite sufficient to maintain the conductivity of the gap at the times of maximum condenser current, so that the spark-train is able to continue until its amplitude falls to quite a low value.

And further, the increased flow of energy across the air-gap, which now includes a little main current, will evolve more heat and lower the gap resistance still more and therefore lessen the rate of decay of the condenser oscillations.

As the condenser discharge dies out, the need for a low air-gap resistance disappears, and the main current can also then die out with advantage so that the air can recover its insulating condition.

Thus we can establish a case why discharge should take place *a little before* the main current reaches zero.

But it is also possible to advance arguments why, under certain circumstances, it may be best to take the discharge *a considerable interval before* the current falls to zero.

It has been shown that the conductivity of the spark-gap is a matter of importance. When a spark passes between two electrodes in air, the air molecules become "ionised," or charged, and in this state they travel across the gap, each molecule delivering up its charge to the electrode of opposite potential. This in a gas constitutes conduction.

The conductivity of the gap will depend on the charge given to the air and the rate at which the molecules travel, and thus will depend on the electrode potential before breakdown.

But if we have to rely on the carrying capacity of the air alone, the conductivity may still remain too low to allow the maximum condenser current to flow through the gap.

The more the air is heated, the greater the mobility of its molecules and the lower its effective resistance, but it is found that the air must be supplemented with metallic vapour if the conductivity required for a high-frequency spark carrying even moderate power is to be obtained. The surfaces of the electrodes will supply this vapour *if the current density is high enough* for the particular metal concerned; and if it can be arranged that only one electrode is heated while the other remains cool, the progress of the metallic "ions" in the spark from the hot electrode to the cold is encouraged.

The average condenser discharge current being anything from 100 to 1000 times the value of the average charging current, will produce practically all the metallic vapour found in the gap, but owing to its rapid reversals it will be unable to maintain the vapour in the state of a conducting bridge, and the gap must depend on the low-frequency main current which is small in value but comparatively constant during the discharge, for this purpose. The greater the volume of vapour present, the greater the main current potential required to control it.

Now, as often happens in a radio transmitting set, in order to adjust for a change of wave-length we may have one condenser arrangement of a given capacity charged to a potential, say, of 10,000 volts, and another condenser arrangement having four times this capacity, charged from the same supply to 5000 volts, and on change-over no alteration is made in the minimum length of the spark-gap.

The product CV^2, or the potential energy in the discharge circuit, will be the same in each case, but although the gap re-istance is required to fall lower for the large capacity circuits with its possible higher current than for the low capacity circuit, there will be a smaller initial potential to ionise the gap and, in consequence, its drop in resistance must depend more on the supply of metallic vapour. But this is not given off by the electrodes until the spark current passes, and requires time to produce.

But if the gap resistance has not fallen sufficiently low within the interval of 1/4 cycle of the H.F. discharge current —which for a 600-metre wave-length adjustment would only be 1/500,000th second—the H.F. current will not be able to rise to its full value.

Then if in the case of the low-capacity circuit the best results are obtained when the main current at the moment of discharge is above zero, when a change is made to the high-capacity circuit, it will often be found advisable to arrange that when the discharge occurs there shall be still more main current in the circuit, in order that it may have a greater influence in maintaining the reduced gap resistance until the discharge ends.

We have next to consider the condition of "resonance" in relation to the spark discharge.

When the spark occurs, and as long as it continues, the condenser practically ceases to receive fresh energy from the charging circuit, as the reactance of the spark will be low compared with that of the condenser. Also, with a good conducting air gap the condenser will not feed back any energy to speak of into the charging mains.

To all intents and purposes, the condenser has been replaced in the charging circuit by the comparatively low resistance of the spark, and if the non-sparking circuit was in a state of resonance, the sparking circuit certainly will not be so, as it practically contains only inductance and resistance.

The current, instead of being in phase with the E.M.F., will change to a lagging condition.

This will immediately lower the efficiency of the alternator and of the circuit as a whole, at the moment when the circuit is giving out most energy and therefore when high efficiency is most required.

Clearly what is required is that the main circuit should be *in resonance when sparking*, in order that the alternator may deliver its maximum energy to the circuit and the over-all efficiency should also be a maximum.

Suppose we make the current *lead* in the non-sparking circuit. Then it would seem possible by trial to find some spark phase adjustment at which the lagging effect imposed on the current just brings it into phase or resonance when sparking takes place. For this condition to be possible a certain proportion of the condenser energy must always remain in circulation in the charging circuit.

Now the term "resonance," as applied to the circuit conditions at the moment of sparking, does not mean that the time period of the circuit agrees with that of the alternating current supply; the periodic time of the supply is so long compared with the short interval of sparking that it scarcely affects the question. It means that the reactance of the condenser in the main circuit during the discharge is equal to the reactance of the inductance.

Suppose OI (Fig. 37) to represent the direction of the main current, OV_L the induced E.M.F. due to inductance, and OV_C the back E.M.F. due to the condenser.

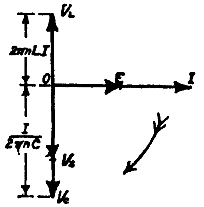


FIG. 37.—Resonance Conditions during Discharge.

If during discharge the condenser potential OV_C falls to $OV_S = OV_L$, then the reactances in the main circuit will balance out and the applied E.M.F., OE, will depend only on the non-inductive load, and so will be in phase with the current.

Then the less the inductance of the low-frequency circuit and the less the main current flowing at the moment of sparking, the smaller will be the proportion of condenser charge retained in the circuit to bring about resonance, and the less will the steadiness of the spark, and therefore the quality of the note, be affected.

A leading current in the non-sparking circuit is the most general case in practice. The inductance in the charging circuit is then *less* than what is required to tune, and the natural period of the charging circuit is therefore less than that of the supply.

The minimum inductance of a radio transmitting circuit is that of its alternator and transformer. If this is high relative to the nominal power of the circuit an unduly large proportion of condenser energy will in consequence be tied up by it, which will result in a weak and unstable spark.

But there are also cases in which a lagging charging current results in the greatest amount of energy being released in the high-frequency circuit on spark.

It has been shown that the current-carrying capacity of the spark depends principally on two factors: (1) the potential between the electrodes before discharge; and (2) the phase of the main current at which the discharge takes place.

Now if the spark occurs before the charging current reaches zero, so much less charge flows into the condenser; and if in order to increase the conductivity of the gap the discharge is taken while there is still a considerable amount of main current flowing, the energy diverted from the condenser will be inconveniently large.

But suppose the charging current is lagging, and the discharge is taken just a little before it reaches zero so that it has been able to deliver almost its full charge to the condenser; then the current will immediately be made to lag still more, which will cause it to rise suddenly, and its reaction on the gap will result in maintaining the good conductivity required for the condenser discharge.

Thus let AB (Fig. 38 (*a*)) represent a half cycle of current—the phase displacement of current relative to E.M.F. being supposed to remain unaltered by the spark—and let CD represent a curve of current having the same lag as the current during the spark; then, when the condenser discharges on its potential reaching the value OB—the alternator still generating E.M.F.—the current rises from the value B to the value P on the more lagging curve, and finally, after the discharge, falls and crosses the zero line along some intermediate curve PR.

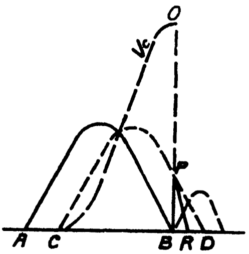


Fig. 38 (*a*).—The Lagging Effect of Spark Discharge.

The condenser potential curve also after the discharge will show a small rise on the same side of zero, produced by the part of the current BPR, but as its maximum value will be insufficient to break down the air gap, this little hump represents condenser charge which will be returned to the circuit and remain circulating in it.

Fig. 38 (*b*) shows typical oscillograms of current and voltage in the high-tension low-frequency circuit when the spark is taken before the L.F. current reaches zero.

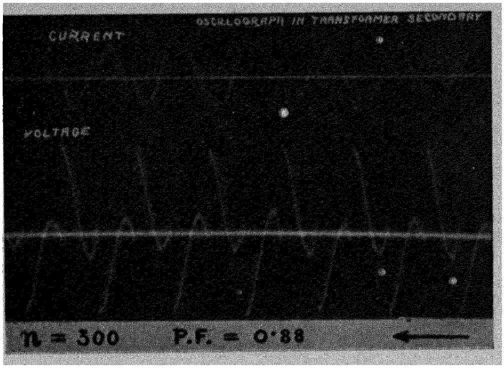


FIG. 38 (*b*).—Oscillograms of H.T. L.F. Current and Voltage when the Spark is taken before the Current reaches Zero.

In this case the circuit is neither in tune when sparking or non-sparking, the inductance in the charging circuit is *more* than is required for resonance, and, in consequence, the natural period of the circuit is greater than that of the supply. It is a condition which is most often met with in high-power radio sets which, although they may have to work with several hundred amperes in the high-frequency circuit, are frequently unable for various reasons to use a higher condenser charging voltage than what is quite normal for low-power sets, and therefore have to rely more on the low-frequency main current to maintain the vapour bridge across the air gap.

The above discussion of the conditions which are introduced by the condenser discharge should make it clear that the most efficient adjustment of any circuit for sparking is in fact peculiar to that circuit and is best found by trial. The main current during the non-sparking period may be either in phase, leading, or lagging, and the phase position for sparking should be somewhere on the slope of the current curve before it reaches zero.

The most efficient type of charging circuit is one in which all the low-frequency inductance required is provided by the leakage fields of the alternator and the transformer, and which applies a high charging voltage to a low capacity. The charging current will then be nearly in phase, and a clean easy spark, giving a clear note of twice the frequency of the alternator, will take place practically at the moment of zero charging current.

The principle of the Marconi Disc Discharger which makes spark phase adjustment possible is illustrated in Fig. 39. Keyed on the shaft of the alternator is a disc of insulating material, having a conducting rim of brass or copper fitted with equally spaced radial metal studs, which correspond in number to the half cycles of alternating current generated per revolution in the armature winding.

In most machines, and as shown in the diagram, the number of studs corresponds to the number of alternator poles.

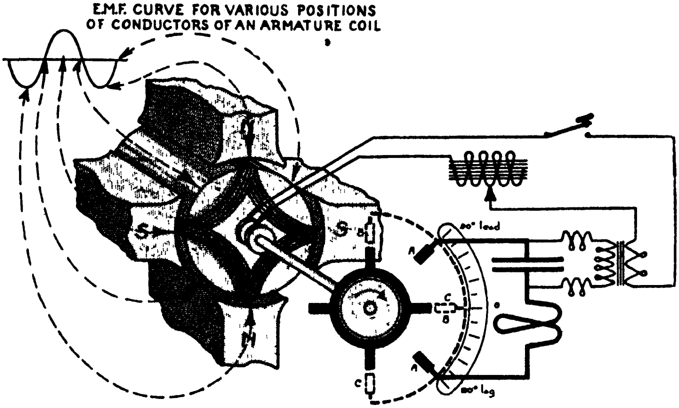

E.M.F. CURVE FOR VARIOUS POSITIONS OF CONDUCTORS OF AN ARMATURE COIL
S
S
N
B
A
C
B
A
C
90° lead
90° lag

FIG. 39.—The Principle of the Marconi Disc Discharger.

In line with any two studs are mounted the two spark electrodes A, which are connected to the condenser.

The electrodes are carried by a rocker which enables them to be advanced, as shown at B, B, or lagged, as shown at *c*, *c*, with reference to any fixed position of the disc studs.

Now we know that when the armature coil, W, on open circuit reaches the position shown, its long sides will be passing through the strongest parts of the field under the two poles and therefore cutting most lines, so that the coil will then be generating its highest E.M.F. Also, as all the coils connected in series in the armature of an alternator reach similar positions relative to the poles at the same time, the total E.M.F. generated by the winding as a whole will be a maximum at this position.

Suppose this E.M.F. is sufficient to produce a spark in air. Then we could connect the alternator slip rings direct to the discharger electrodes and rock the electrodes so that they came into line with the disc studs when the armature conductors were cutting most lines. They would then be set for a spark to take place at the peak of the alternator voltage curve.

If the electrodes were rocked a little further back, against the direction of revolution, they would be in a position to take a spark on the rising part of the E.M.F. curve, and alternatively if they were rocked a little forward in the direction of revolution they would take the discharge on the falling part of the E.M.F. curve.

The E.M.F. generated by an armature conductor in travelling from the position in which it cuts the maximum field under a north pole, to the position in which it cuts the maximum field under a south pole, passes through 180 electrical degrees, from the positive peak of the E.M.F. curve to the negative peak, and the electrodes, when rocked through the same angle, that is, from the centre of one disc stud to the centre of the next, will displace the phase of the spark discharge by the same amount. It is therefore usual to fix a scale on the rocker divided into 180 phase degrees, which spans exactly the angle between the centre lines of two neighbouring studs, and to fix a pointer on some non-moving part of the machine which indicates on the scale the approximate phase position at which the spark takes place relative to the E.M.F.

A typical scale is shown in Fig. 40. It has a central zero, and increases *in* the direction of rotation to 90° lead, and *against* the direction of rotation to 90° lag. The relative positions of "lead" and "lag" on the scale are explained by the fact that the pointer is fixed and the scale is rocked with the electrodes. If the pointer, instead of the scale, were attached to the electrodes, the markings "lead" and "lag" would have to be reversed. The adjustment of the index to the scale is such that if the spark is taken with the index set at 0° it will occur at the moment of maximum alternator E.M.F.; but if, for instance, the electrodes are rocked so that the index shows 30° lag on the scale, the spark will occur 30° of phase *after* the E.M.F. has reached its maximum value, and so on.

In most cases the alternator voltage is too low to cause a spark in air, and to obtain one it would be necessary to use a potential transformer. Now the transformer secondary potential lags almost 180° in phase behind the terminal potential applied to the primary; and if the drop due to circuit resistance is negligible, the primary potential will be in phase with the alternator E.M.F., so that the setting of the disc electrodes to obtain maximum spark with the transformer—if due allowance is made for the length of arc jumped by the spark—will be found to correspond with the position required without the transformer.

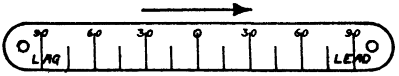


FIG. 40.—Scale of Spark Phase.

The next step is to add the condenser to the secondary circuit of the transformer. If the circuit is in resonance before sparking, and if, as already explained, the charging current is not required to aid the discharge current in lowering the gap resistance, we shall now find that the best spark phase position as shown on the scale is very nearly 90° lag.

Such is the ideal condition illustrated in Fig. 36, the discharge taking place when the charging current and E.M.F. have both fallen to zero; but, as we have already seen, there are many factors affecting the discharge in practice which may cause it to occur at almost any phase position relative to the alternator E.M.F.

In general the spark occurs just as the charging current approaches zero, and, as the "in-phase" sparking position is shown on the scale as 90° lag, a best spark phase position between 0° and 90° lag on the scale will indicate a *leading* charging current, and between 90° and 0° lead a *lagging* charging current.

The size of the electrodes and the section of the studs must be such that in the very short time the spark lasts the high-frequency current vaporises them sufficiently quickly to give the necessary power-carrying capacity to the spark.

As the spark takes place between the nearest conducting points (Fig. 41 (*a*)), these ultimately burn away, leaving wedge-shaped ends (Fig. 41 (*b*)).

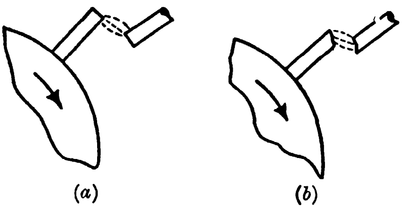


FIG. 41.—The Burning Action of the Spark on the Electrodes.

If the studs are too large in diameter, they will not heat up quickly enough, and the spark and the output will be poor.

If, on the other hand, the studs are too small in diameter, they will burn away too quickly, and will require frequent readjustment of the minimum gap distance and frequent renewal. More heat will be generated in them than they can dispose of by radiation, and their increased resistance in consequence will lower the efficiency of the high-frequency circuit.

Whenever the design of the set will allow it, revolving copper discs are used as electrodes, which present a constantly changing edge for the spark discharge. Their average temperature is low, and heat radiation good, so that they maintain a fairly low resistance and require much less adjustment and renewal.

The precision of the spark phase adjustment—particularly as regards the moment when the sparking stops,—as will be seen from Fig. 42, depends on the thickness of the studs and electrodes and the distance the condenser potential will jump through air. As the disc revolves and the studs approach the electrodes the spark jumps forward to meet them, so that unless the setting of the rocker scale has been adjusted on spark the pointer reading on the scale will show a more lagging phase position than is actually the case.

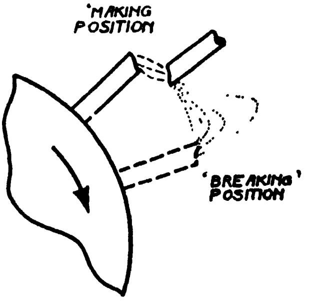


FIG. 42.—The Spark on "Make" and the Arc on "Break."

Also in this connection the *windage*, or air draught on the spark—produced either naturally by the rotation of the disc, or artificially by means of a fan on the same shaft, or a separate blower—may play an important part.

During the discharge the studs approach closer to the electrodes, the potential required to maintain the conducting gap becomes less, the metallic vapour produced bridges a much smaller space, and the whole time there is a current of air in the direction of the disc rotation. After an interval depending on the width of the passing conductors, the spark gap increases, the vapour cools and dissipates quicker than it is renewed, and finally there is a sudden break in the spark, and the air in the gap once more becomes an insulator.

The moment of interruption of the discharge is necessarily of considerable importance.

Take two extreme cases. The high-frequency currents—particularly those of long period, having a wave-length, say, of 10,000 metres—may be interrupted by the rotation of the disc before the condenser energy has been completely dissipated, due to the individual or combined effect of (1) the narrow width of the sparking surfaces, (2) the short jumping distance through air of the condenser potential, and (3) excessive windage.

Too much air draught will keep the electrodes cold, or disperse the conducting vapour too quickly for efficient working.

Or, again, the high-frequency currents—in this case more particularly those of short period, having a wave-length, say, of 300 metres—may have died out, leaving the main current still flowing across the air gap, and, after passing through zero, continuing as a rising current short-circuiting the condenser, as a result of (1) large section of studs, (2) long jumping distance of the condenser potential, or (3) insufficient windage, or possibly a combination of these causes.

Low-power sets seldom require an auxiliary air draught on the spark, but for high-power sets it is essential.

The Marconi-Mackie Disc Discharger illustrated in Fig. 43 is designed for a 60-kw. transmitting set, to give 600 sparks per second.

The main disc is of solid copper, having a diameter over the studs of 36 inches. It is mounted in ball-bearings, is fitted with a flexible coupling for direct drive from the motor-generator, and is carefully balanced to run without vibration at its working speed of 1500 r.p.m.

It has 24 copper studs which are screwed and pinned into the periphery; they project 5 inches, and have a diameter of 1 inch.

The electrodes—generally called "side discs"—are discs of copper, 12 inches in diameter, and $\frac{3}{4}$ inch thick, which are driven by a system of rods and bevel gears from the main shaft through a flexible coupling.

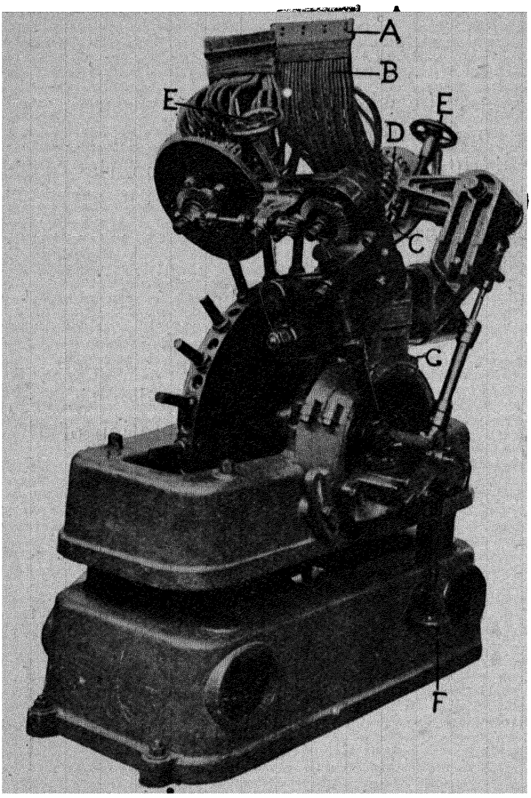


FIG. 43.—The Marconi-Mackie Disc Discharger.

The H.F. connection from the bus-bars to the side discs is made first through strips of sheet copper, A, which are bolted to the bus-bars, thence through a number of flexible stranded copper connectors, B, to a cast brass plate, C, carrying a number of brass fine-wire brushes, D and these brushes bear in a circular shallow groove in each rotating side disc.

The minimum spark-gap length can be controlled by the adjusting screws E, and the insulated cast-iron frame which carries the side discs can be rocked for spark phase by manipulating the handle F; the final adjustment being shown by the scale and pointer G.

The Calibration of the Disc Discharger for Spark Phase, when it is mounted on the shaft of the alternator or otherwise rendered synchronous, consists in first finding the position of the rotor at which maximum E.M.F. is generated, then rocking the electrodes so that they come opposite the disc studs at this position, and, finally, at the same setting of the electrodes, fixing the pointer on the machine so that it indicates 0° lag or lead on the electrode rocker scale of phase degrees which has already been described.

To find the rotor position of maximum E.M.F., connect a telephone permanently across the alternator slip rings, excite the field of the alternator at normal voltage, and then turn the rotor slowly by hand, noting that position at which the telephone gives no sound. This position will be that of zero E.M.F. Continue to rotate it until a second position of zero E.M.F. is found.

The position of the rotor for maximum E.M.F. will then be midway between these two.

This method is not suitable for large machines, as the inductive kick on breaking the field circuit may be bad for the insulation of the winding, and the small arc which results makes the determination of the position of no sound less exact.

For large machines, therefore, the exciting circuit is completed through a rheostat or an ordinary field regulator, and the exciting current is varied rapidly by means of the rheostat so as to produce a noise in the telephone, when, as before, the position of the rotor at which no noise is heard in the telephone will be the position at which no E.M.F. is generated.

Alternatively a milliammeter could be used in place of the telephone. On varying the field regulator, the instrument needle will give a kick until the rotor is in the correct position for zero E.M.F.

Another method which takes into account the distance jumped by the spark discharge from the electrodes to the approaching studs is as follows:—

The secondary terminals of the transformer are connected to the disc with the transmitting condenser disconnected, and a resistance is inserted in the primary circuit to limit the current so that it does not exceed the normal when the circuit is closed and the transformer secondary is sparked.

The alternator and disc are then run at normal speed, and the maximum spark lengths obtainable across the two gaps between the electrodes and the disc studs are observed. Usually one gap is varied, the other being kept a constant length. This process is repeated for various positions of the electrodes, and a curve is plotted connecting angular position of electrode rocker and spark length. The position at which the curve reaches its maximum should then be noted.

Now the spark is equivalent to a non-inductive resistance, so that the current in the spark will be in phase with the transformer secondary potential. The secondary potential lags about 180° behind the potential applied to the primary terminals, which—provided the resistance drop in the circuit is negligible—will be identical with, and therefore correspond in phase with, the machine E.M.F.

Then the disc position for maximum spark length, if no condenser is connected across the transformer secondary, will also correspond for all practical purposes with the rotor position for maximum E.M.F.

How to adjust the Spark Phase.—If possible the spark phase should be adjusted while the alternator is running and the load is on.

The capacity of the condenser is fixed, and if no variable inductance is provided, the alternator should be run at a speed which is estimated to give the correct frequency for the circuit. The electrodes should then be rocked to that position which gives the strongest spark having the purest musical note. Such a spark indicates a condition of greatest energy in the high-frequency circuit for a given alternator excitation, and highest over-all efficiency input to output.

Then another frequency of the alternating charging current should be tried by altering the speed of the machine, and the adjustment of the spark phase should again be varied by rocking the electrodes, until the best results are obtained, as before. If the circuit conditions have thereby been improved, the spark will be stronger and the over-all efficiency will be greater.

Proceeding in this manner, the peak of the efficiency curve can be found. The readings on spark of a reliable wattmeter in the low-frequency charging circuit are at all times a good enough guide, or failing that, the sound and appearance of the spark.

For the discharge, as we have said, consists of two superimposed currents—(1) a large current composed of a number of trains of high-frequency oscillations, which, because they start at regular but widely separated intervals, and the current in each train grows quickly to a maximum, produces a brilliant spark having a clear, well-defined note; and (2) a small current of the same frequency as the supply, which is inclined to be irregular and grows and dies at a much slower rate, and as a result does not produce a clean-cut note.

Then if the spark phase is altered until the best audible note is obtained, this will be the condition of best compromise of greatest high-frequency and least low-frequency current in the spark gap.

But very often the alternator speed cannot be varied except between narrow limits, or there may be reasons—such as the need of a definite note frequency—why it should be kept constant. The alternator is then designed so that it has an inductance less than that which is required to produce resonance in its working circuit at the given frequency, and an adjustable inductance is provided for tuning.

For each value of tuning inductance inserted there should be a different spark phase position which gives best results, and which has to be found by trial.

The maximum output cannot be equal to that of the circuit tuned without additional inductance by varying the speed of the alternator, and if a definite output on spark is required a compromise adjustment may sometimes be found best which uses less inductance than is required to give the highest efficiency obtainable on spark, because it allows a larger output to be obtained from the alternator.

A Marconi 60-kw. Spark Transmitting Set is illustrated in the frontispiece. The alternator A drives a synchronous disc discharger of the type shown in Fig. 43, by means of an insulating coupling which is fitted through the wall of the brick silence cabin D. The main bus-bar connections from the jigger and condenser to the disc are shown entering the cabin at B. The jigger primary is marked P, and the bank of glass-plate condensers in oil-sealed porcelain pots, C.

The jigger secondary is shown at S, and the aerial tuning inductance at L_A.

The Plain Discharger.—Having now examined the conditions which prevail when it is possible to time the moment of the discharge with some degree of precision, we can consider briefly the more complicated case presented by the fixed air gap of the plain discharger.

The instant and frequency of discharge are controlled—

(1) By the length of the spark gap.

(2) By the tuning of the charging circuit.

(3) By the conductivity, or ionisation of the air gap.

A spark takes place as soon as the potential on the condenser has risen to the value required to break down the air insulation. If the circuit is in resonance before the discharge takes place, then it will be seen from Fig. 44 that the spark length as given by the ordinates A, B, C, D, or E of the condenser applied potential curve V_C, also determines the spark phase, that a small spark will be accompanied by a rising current, and a large spark by a falling current.

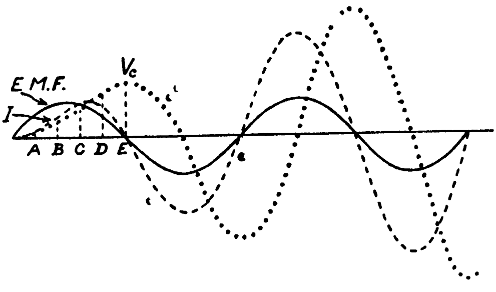


Fig. 44.—The Discharge Conditions across a Fixed Gap.

As a rising main current on spark is to be avoided, when using an air gap which is much less than the sparking limit better results can be obtained by mis-tuning the circuit so as to produce a lower maximum potential on the condenser. The spark will then take place at a more advanced point on the current curve. A spark will pass every time the condenser potential during the half cycle rises to the critical value for the air gap, and best results will be obtained if the time period of the circuit is made to agree with this rate of discharge.

For these two reasons a leading current is best for small gaps.

But if there are many sparks per half cycle the value of the main current passing through the gap, and therefore the gap resistance, will be different for each spark. Also it follows that the condenser charges will be irregular in time and in quantity.

The discharge becomes more regular with increase of gap length up to that which allows one discharge to take place per half cycle—the tuning being at the same time adjusted to suit the rate of sparking.

For a gap which is greater than can be broken down by the maximum condenser potential which results from the first half cycle of charging current, the circuit works best when it is tuned for a spark once per cycle, and the charging current in consequence is then lagging.

Air which has once been subjected to sparking breaks down easier a second time, so that unless the used air is removed after each discharge the insulation of the gap will be variable, and irregular sparking will be encouraged.

An air blast applied to a spark will therefore cause it to be more regular in frequency and voltage, and the main current in it will be less; but if the blast is too strong, the gap resistance during the discharge will remain high, and the high-frequency oscillations may as a result be damped out quicker than is required.

The "Quenched Spark" Discharge.—The H.F. circuit we have so far been considering, P (Fig. 45), is that in which the oscillations are generated. Having a "closed" character it is not suitable for radiating energy into space, and it is therefore linked by means of a magnetic coupling at K—or sometimes a capacity coupling—to a secondary circuit of an "open" type, the aerial AE, which is better able to fulfil this function. The two circuits are tuned to the same frequency, and energy passes through the coupling from one to the other.

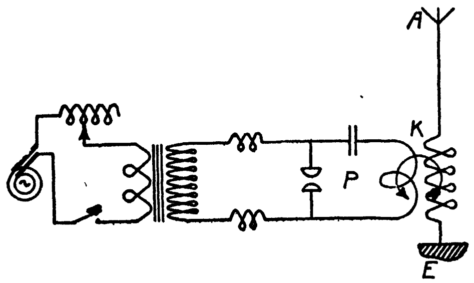


FIG. 45.—The Coupling of a Radiating Circuit to the Condenser Discharge Circuit.

When the aerial circuit is excited, it is able to react back on the primary through the same coupling. As will be explained later, this leads to the generation in both circuits of currents of two frequencies, one greater and one less than that of either circuit oscillating alone, which superpose and produce a beat effect. In this regard compare (*a*) with (*b*) and (*c*) in Fig. 46.

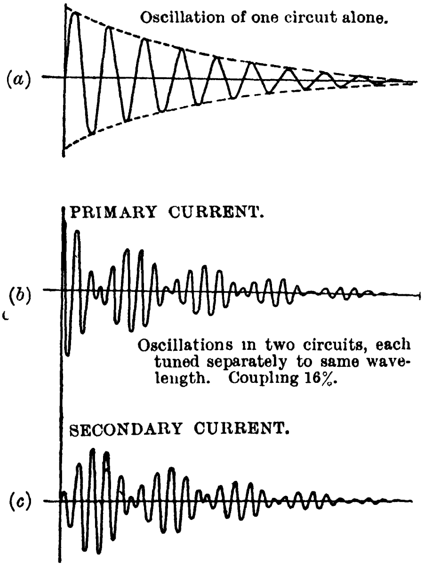


FIG. 46.—Slightly Damped Oscillations in Two Tuned Coupled Circuits.

If this reaction is to be avoided—and purity of frequency, or its inverse measurement "wave-length," is of great importance in limiting interference between radio transmitting stations—either the coupling must be made very weak or loose, in order that the two waves may be close together and the beat frequency low, or else the circuits must be arranged so that the coupling acts as far as possible like a valve, transferring energy from the primary to the aerial circuit, but not from the aerial circuit back to the primary.

Marconi practice employs the first method for general work, but under certain conditions the second method which we shall now discuss has its advantages.

Its application consists in transferring as much energy as possible from the primary circuit to the aerial in the first few swings of current, which current by the employment of a special form of spark gap is made to die out very quickly, so that the impulsed aerial continues its oscillations uninfluenced by the primary (Fig. 47 (*a*) and (*b*)), and therefore radiates a pure wave.

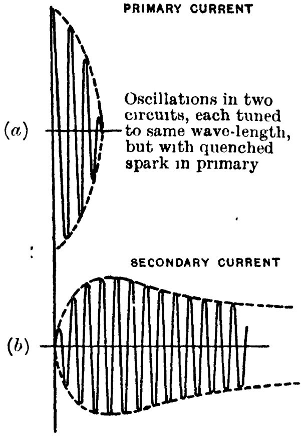


Fig. 47.—The Effect of strongly damping the Oscillations in one of the two Coupled Circuits.

The process of setting the aerial oscillating in this manner is known as "shock excitation," the quickly damped out discharge of the primary circuit as a "quenched spark," and the type of discharger which produces this effect a "quenching gap."

In order that the primary H.F. oscillations may die out quickly, the air-gap resistance must remain high. To prevent it being lowered too much by the presence of metallic vapour, the temperature of the electrodes must be maintained so low that it is difficult for the vapour to be produced by the H.F. current. As local heating is to be avoided, the spark must not be confined to one spot on either electrode. It should be free to take place with equal ease anywhere over a large surface. The weak, low-frequency current, which flows during the discharge, can then be easily quenched by the fall of potential across the gap with the growth of the high-frequency current, as the potential finally reaches a value which is insufficient to maintain a conducting bridge between the electrodes. The air gap will then resume its non-conducting state after each alternation of H.F. current, or separate spark of a train; the charged gas molecules, the positive from one electrode and the negative from the other, will all give up their charges to the oppositely charged electrodes, or else combine with each other in the air gap, or dissipate in space away from the electrodes so that they become unavailable for conduction.

In the Telefunken type of discharger (Fig. 48), the electrodes E are heavy copper plates, which are sometimes provided with channels, C, through their thickness for an air blast. They are also flanged, as shown at F, to encourage heat radiation. As an ionised gas can get rid of its charge most completely and quickly in a small gap, the discharger consists of a number of small gaps in series, one gap of ·15 mm.—the distance being fixed by a mica spacing washer M—being allowed for each 500–700 volts of condenser potential.

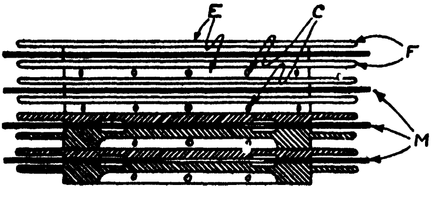


FIG. 48.—The Telefunken Type of Quenching Gap.

If an insufficient number of gaps is used there will be no true quenching after each alteration of H.F. current, and coupling effects will become apparent. The supply current will continue to flow, and H.F. currents of two frequencies will be generated. The spark will get localised, the electrodes will heat up and their surfaces will show wear. Also, if too many gaps are used, the discharge will be irregular, and again coupling effects will be present. There is, however, enough latitude for easy adjustment between these extreme cases.

If the electrodes are pure copper, pimples of copper oxide may form and short the gap. This is avoided by silver-plating the surfaces.

The surfaces must be kept truly plane and parallel, and any unevenness must be immediately ground, or cleaned, or polished off.

As the primary transfers all its energy to the aerial in a very few oscillations, the coupling must be fairly tight—about 20 per cent. If it is too tight, sufficient energy is fed back to the primary circuit to prevent quenching.

Hydrogen, being a very light gas, is more mobile than air. It can therefore get rid of its charge quicker, and in consequence is better as a quenching agent. Also an air draught through the gap by removing the ions would encourage quenching, but the blast must have a pressure of about 100 lbs. per square inch to be truly effective.

Quenched Spark Discharger, Marconi Type (Fig. 49).—This consists of a series of copper plates having heavily silvered ring sparking surfaces, A, which are truly plane, the edges of these surfaces being gently cambered, in order to ensure a gradual decrease in the intensity of the electrostatic field where the gap between the plates commences to widen.

There are three alignment rods of heat-resisting insulating material, B, which pass through holes in the grooves and keep in place the mica spacing washers, C, which rest on the inner raised rings, D.

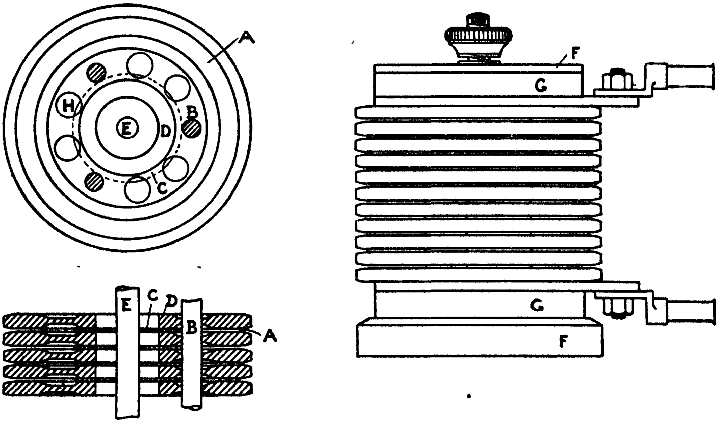


FIG. 49.—The Marconi Quenched-Spark Discharger.

A copper rod, E, passes up through a clearance hole along the axis of the discharger, and is fitted with nuts for clamping the brass end plates, F, which are separated from the copper sparking plates by thick discs of insulating material, G.

Ventilation holes, H, are carried right through the discharger, and the discharge is open to the air.

Fig. 50 shows an interesting series of tuning curves obtained with this gap.

The curve (4) was obtained with the primary circuit in tune with the secondary circuit, the coupling between them being about 20 per cent.

Curves (3), (2), and (1) resulted from mis-tuning—the aerial circuit having its wave-length progressively *decreased*

4 per cent, then 10 per cent, and finally 16 per cent from in-tune, the coupling remaining about the same.

The improvement in the direction of single-wave transmission is indicated by the increased peakiness of the curves.

Now when an alternating current is applied to a coupled circuit, the mutual inductance is alternately added to, and subtracted from, the separate circuit inductance values (see pp. 219-221); so that if we consider the case in which resonance takes place, currents of two frequencies are produced, one higher than the natural frequency of either circuit, and one lower.

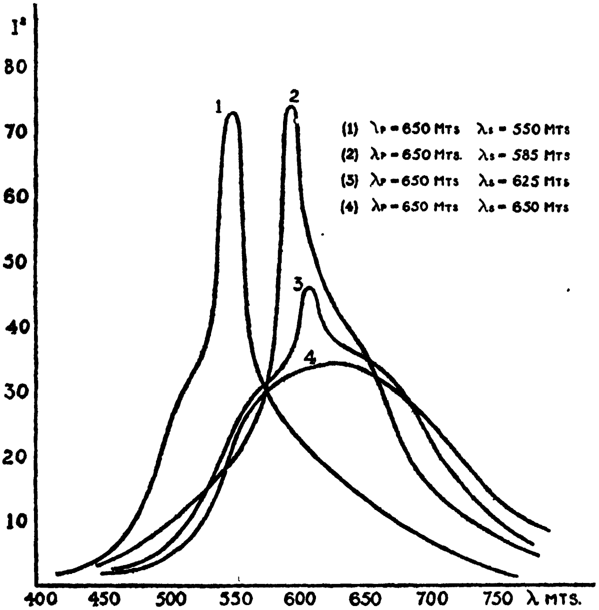


FIG. 50.—The Effect of De-tuning the Aerial Circuit.

The higher-frequency current results when the secondary circuit—which may be an aerial—is either storing, consuming, or radiating the energy received from the primary; and the lower-frequency current when the secondary circuit is returning some of its energy to the primary.

The less it is able to return, the weaker will be this current of lower frequency.

The improvement in quenched gap working, remarked on above, takes place when the natural frequency of the aerial is displaced towards the higher frequency, or shorter wave-length, produced by in-tune coupling, which has the effect of encouraging the reception of energy, while it discourages its return.

Under such a condition the aerial is in a more favourable state for true *impulse* excitation.

The degree of mis-tuning necessary varies with the coupling and the circuit decrements. Under certain conditions best results are obtained by *increasing* the wave-length of the aerial.

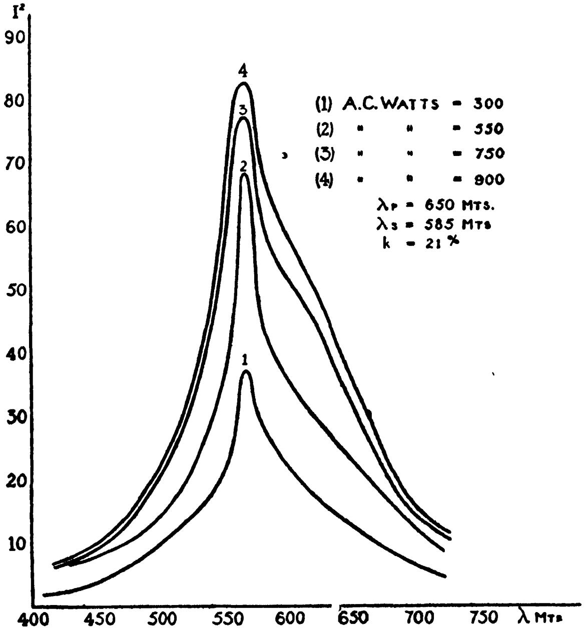


FIG. 51.—The Effect of increasing the Power in the Condenser Circuit.

The series of curves in Fig. 51 shows the behaviour of one of these gaps as the power in the primary circuit is increased from 300 watts to 900 watts, the coupling being about 21 per cent and de-tuning 10 per cent.

At the higher power, the tuning curve shows a tendency to bulge, or form a second hump, not far from the peak, which indicates that the power limit for efficient quenching for this particular size of gap is being reached.

CHAPTER IV

CONTINUOUS WAVE TRANSMITTERS

The High-Frequency Alternator.—Its Working Range of Frequency.—Two General Types of Low-Frequency Alternator.—The Design Limitations on Frequency.—The Duddell 2000*-cycle Alternator.—The Alexanderson* 100,000*-cycle Alternator.—The Principle on which it works.—Definition of an "Inductor."—Cross-section through the Machine.—Relation of Armature Winding to Inductor Spokes.—The Step-up Gear.—The Bearings.—Electrical Constants of the Machine.—Scheme of Connections to the Aerial.—Correction for Speed Variation.—Stator Winding of Alexanderson* 200,000*-cycle Alternator.—The H.F. Alternator of the Société Française Radio-Electrique.—General Description.—The Goldschmidt Alternator.—Principle on which it works.—The same Principle active in Standard L.F. Alternators, but not encouraged.—The Phase Relationships of the Currents of n,* 2*n,* 3*n, and* 4*n Cycles in the Stator and Rotor Windings.—Comparable with Conditions in a Static Transformer.—Losses Accumulative with Increase of Frequency. The H.F. Alternator at Hanover.—Scheme of Connections to the Aerial, —For* 40,000 *Cycles—For* 60,000 *Cycles.—Static Frequency Changers. —The Magnetisation of Iron,—By Direct Current—By Alternating Current.—Hysteresis,—By Direct and Alternating Currents through separate Windings on the same Iron Core.—Current and Flux Curves.—Method of Vallauri and M. Joly for Doubling the Frequency. —Transformer Connections.—Current, Flux, and Potential Curves.— Method of M. Joly for Tripling the Frequency.—Current, Flux, and Potential Curves.—The Marconi "Timed Spark" Method.—Normal Spark Discharge.—The Effect of superposing Wave-Trains which are out of Step; the Oscillations in the separate Trains being maintained in Step. —The "Trigger Spark" Method of Timing.—A "Timed Spark" C.W. Transmitter with one Disc and four Discharge Circuits.—Four Discs in Series in each of four Circuits for High Discharge Voltages. —The Arc Transmitter.—The Duddell Arc.—Similarity of the Arc and Condenser Characteristics—Suggested Method of Operation of the Duddell Arc.—The "Static" and "Dynamic" Characteristics of an Arc.—The Duddell Arc Current.—The Duddell Arc Characteristics.— Range of Frequency and Efficiency.—The Improvements introduced by V. Poulsen.—Air and Hydrogen Arcs.—The Poulsen Arc Current and*

Potential Curves.—The Poulsen Arc Working Characteristic.—The Effect of the Magnetic Field on the Arc.—The Poulsen Arc.—Aerial Connections.—The Method of Signalling with an Arc Transmitter.—The Marconi Expansion Chamber.—A 25-kw. Marconi-Poulsen Arc Transmitter.—The Valve Oscillator.

We shall now briefly review some of the principal methods adopted to excite the transmitting aerial by means of a continuous, instead of an intermittent, supply of energy.

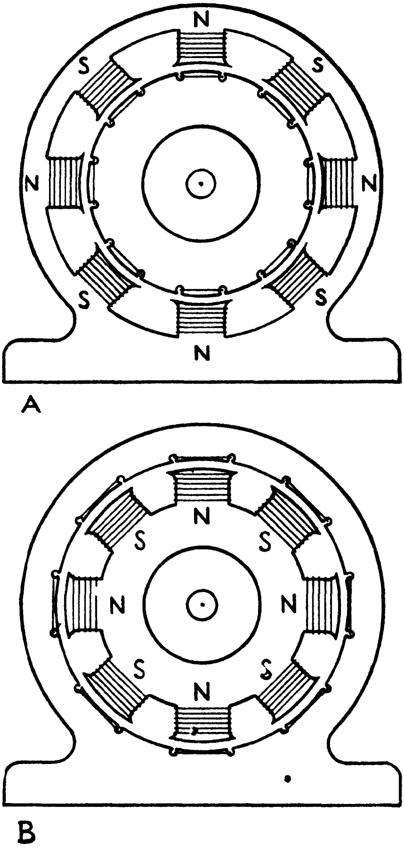


Fig. 52.—Two Forms of Low-Frequency Alternator.

The High-Frequency Alternator.—The problem of building an alternator to produce currents of a frequency high enough to cause resonance in a typical aerial circuit, consists in constructing it so that the current frequency lies within the range 10,000 per second to 1,000,000 per second, the former being the present practical limit for large power station aerials—natural wave 30,000 metres,—and the latter a mean value for ship aerials—natural wave 300 metres.

The usual form of commercial alternator either follows the design shown in Fig. 52 (A), in which the magnet system is the stationary part or "stator," and the armature the moving part or "rotor," or else the design shown in Fig. 52 (B), in which the magnet system is the rotor and the armature the stator; and the alternator frequency is determined by the number of times per second the same coil in the armature is exposed to the influence of a complete cycle of change of magnetic field as produced by the relative motion of the two parts of the alternator.

The frequency thus depends on the number of pairs of poles in the machine and the number of revolutions of the rotor per second.

It is obvious that there is a practical limit to the number of poles with their respective windings which can be crowded round the periphery of the magnet system, and also that there is a safety limit to the peripheral speed of the rotor, which must be considerably lowered by the presence of windings.

Other difficulties met with in the design of H.F. machines are, that all "eddy current" effects—which are produced by changes of magnetic field affecting other conducting parts of the machine besides the windings—absorb energy in proportion to the square of the frequency; and that hysteresis loss in the iron increases as the 1·6 power of the frequency; also that the reactance of the armature winding ($2\pi n L$) increases directly with the frequency, so that for a given size of machine, if the same output is required, and the same potential drop across the alternator on load, the armature inductance must be made inversely proportional to the frequency.

It can be readily understood that if the frequency is increased while the armature inductance remains the same, a value of frequency can be found at which the whole E.M.F. generated is only just sufficient to drive a current against the back E.M.F. of the winding, in which case the machine will give no output. No more than the absolute minimum number of turns are therefore used in the armature coils.

The Duddell 2000-cycle Machine (Fig. 53), designed to produce currents of telephone frequencies, is an illustration of the best which has been done with the more usual form of alternator. It follows generally the scheme of Fig. 52 (B).

The rotor has 30 salient poles cut out of the solid, which carry the former wound field windings. It has an over-all diameter of 20 cm., and runs at a maximum speed of 8000 r.p.m., so that its peripheral speed is roughly 84 metres per second. The construction and balancing must be very carefully done, in order that the rotor may run with safety at a speed of this order, and every connecting lead must be lashed rigid.

The stator is a smooth-surface laminated-iron ring, provided with a gramme-ring winding. The area of each pole face is 1·2 cm. by 5·0 cm.; the inductance of the armature winding 0·01 hry.; and the maximum output of the machine at 2000 cycles, non-inductive load, 5 amperes at 100 volts.

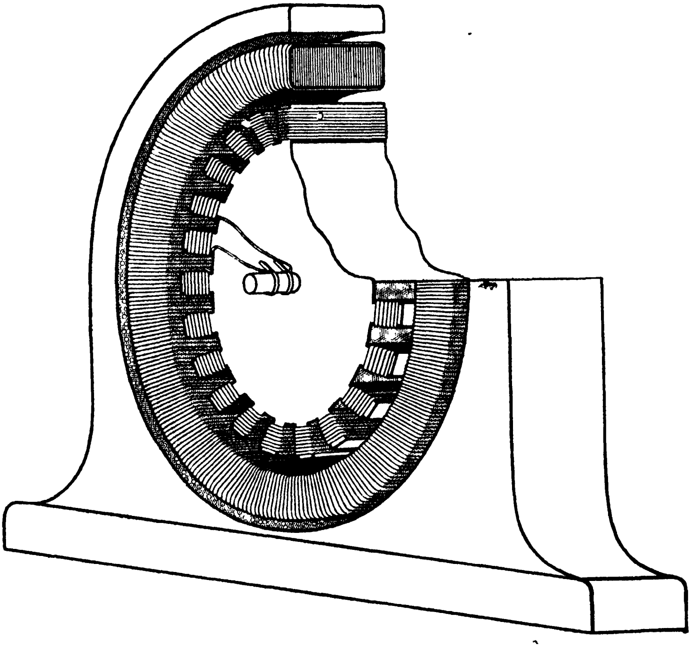


Fig. 53.—The Duddell 2000-cycle Alternator.

But if we relieve the rotor of all windings we can safely run it at a much higher peripheral speed, particularly if the rotor is given a figure of strength. Even 300 metres per second may be well below the bursting speed.

Also if the alternator can be constructed so that the frequency is limited not by the spacing of the poles but by the width of the armature coils, as it is possible to construct very narrow coils we can by this means very much increase the number of cycles per revolution.

The Alexanderson 100,000-cycle Alternator is a good example of a machine which embodies these features.

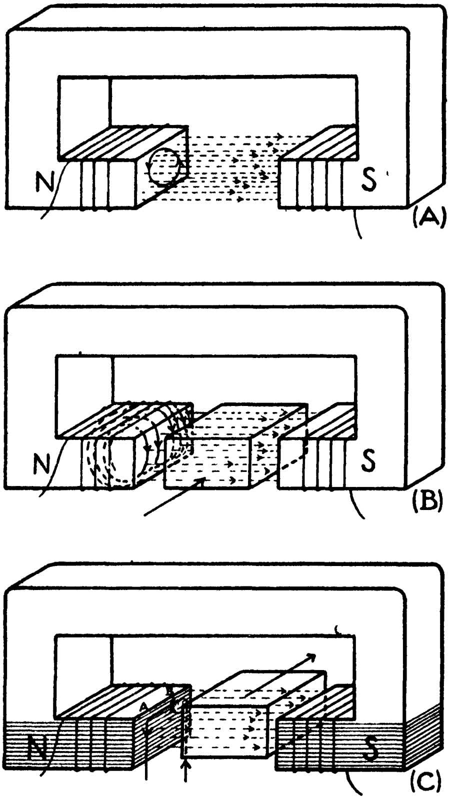


Fig. 54.—The Principle of the Alexanderson High-Frequency Alternator.

The principle on which it works may be briefly explained as follows:—

We have shown that the growth or dying away of a magnetic field will produce an E.M.F. in space at right angles to the direction of the field, and that this E.M.F. will give rise to a current in any closed circuit conductor placed in a suitable manner in the changing field.

In Fig. 54 (A) NS is an electromagnet. If the strength of its field is altered by varying the current through the winding, circulating or "eddy" currents will take place in the faces of the two solid poles, as they are surfaces of conductors in planes at right angles to the direction of the field. Now suppose the magnetising current remains unaltered, but a block of iron is inserted in the air gap so as to almost fill it (Fig. 54 (B)), then the magnetic field in the air space which still remains will be very greatly increased, and while it is increasing an E.M.F. will be induced in each pole face tending to cause currents to flow at right angles to the direction of the field, and also at right angles to the direction in which the block was moving when it was inserted between the poles; such currents finding return paths through those parts of the pole face away from the iron block from which the block has had the effect ot diverting the magnetic flux.

If we wish to prevent such currents we must destroy the re-entrant nature of the conductor—we must laminate it; or, alternatively, if we wish to make use of such currents, it is best to construct a special path for them in which they can be controlled. A properly insulated and re-entrant conductor, laid in a channel cut through the polar laminations, will experience all the reaction due to induced E.M.F., while there will be no useless currents in the pole faces outside the conductor.

In Fig. 54 (C), if the iron block moves in the direction of the arrow from the part of the laminated pole face marked A to the part marked B, the field at A will be weakened while at B it will be strengthened, and E.M.F.'s will be generated which will have a tendency to cause currents to flow at right angles to the direction of motion of the iron and the direction of the magnetic field—downwards where the field diminishes at A, and upwards where it increases at B. Then if we embed conductors to carry these currents in slots cut in the laminations and join them as shown, when the external circuit is completed the movement of the iron will cause a current to flow through this circuit.

A mass of iron, such as the block referred to above, which produces by its movement a variation in the strength of an existing magnetic field, is called an "inductor."

Now Alexanderson has multiplied the unit generator just described—consisting of an electromagnet, two conductors embedded in each laminated pole face, and an inductor of half the width of the pole face—some 300 times to produce his alternator, the description of which is as follows.

The rotor C (Fig. 55) is a chrome-nickel steel disc, 12″ diameter, which acts as an inductor. It is so shaped, that, from a small radius to the periphery, the internal strains on the material when in motion, due to centrifugal force, are everywhere the same, and therefore if the material is homogeneous it will have equal strength everywhere within the limits given.

Near its edge are 300 radial slots leaving 300 radial spokes $\frac{1}{8}$″ wide. Each spoke and slot constitutes one inductor unit. In order to reduce air friction to a minimum, a non-magnetic material—phosphor bronze wire—is riveted into the slots so that the surfaces of the disc are perfectly smooth.

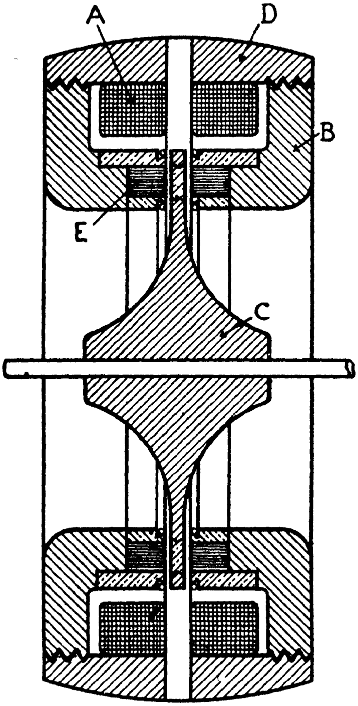


Fig. 55.—The Alexanderson 100,000-cycle Alternator in cross-section.

The stator consists of the cast-iron frame of the machine, D, which acts as the yoke of the field magnet, and is threaded to take the two circular pole rings, B, each fitted with a magnetising coil, A. As the pole rings can be screwed in or out, the gaps between them and the inductor are therefore adjustable.

The armatures consist of laminated iron strip, E, riveted between two brass clamping rings which are screwed to the face of each pole ring. The iron strip is slotted radially to take the armature winding. This winding does not consist, as is usual, of a number of separate coils connected in series, but of a number of separate conductors, A, B, C, etc. (Fig. 56), which are independently subject to induction. They are so spaced that when one comes opposite a spoke of the rotor the next one is opposite a slot, and in order that the E.M.F.'s induced in them should assist each other, the end connections join the conductors in series in a zigzag manner. Each pair therefore represents an elemental coil.

The speed of the rotor is 20,000 r.p.m., so that its periphery moves at the rate of 1000 feet per second (= 330 metres per second), at which it is said still to have a safety factor of 6.

This high speed is obtained by means of a double helical gear —in the gear case G (Fig. 57) —which has a ratio of 10 : 1, the driving motor, M, having a speed of 2000 r.p.m. The alternator is marked A.

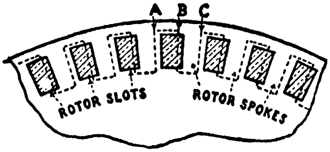


FIG. 56.—The Alexanderson 100,000-cycle Alternator: Relation of Armature Winding to Stator Spokes.

The length of the working air gaps between the rotor and the armatures may be anything between the minimum clearance usable with safety, namely 4 mils, up to 15 mils. It is advisable to adjust the two gaps so that the terminal voltages on the two armatures are equal.

If the electrical balance is not perfect, and the air gap is small, the thin edge of the rotor may be deflected over to one side at full speed, and foul and strip the armature.

The rotor shaft is driven from the high-speed gear through a universal coupling; thrust, T, and steady bearings, S, of special design are used, together with a compensation device, C (Fig. 57), which comes into play if either thrust bearing heats, or forces acting on the rotor for any reason tend to make the air gaps variable. The end play allowed by the bearings is not more than 1 mil.

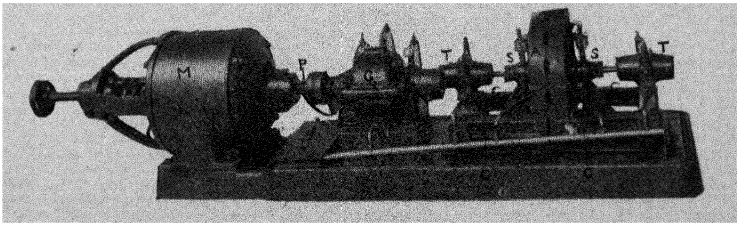


FIG. 57.—The Alexanderson 100,000-cycle Alternator: View of Set complete—Motor, Gear-Box, and Alternator.

A small centrifugal pump driven by the chain, P, is provided for forced lubrication.

The maximum output is, of course, obtained when the capacity reactance in the external circuit is of such a value that it balances the inductance reactance of the alternator at the working frequency, that is when it causes resonance in the circuit. The inductance of the armature winding is about 9·24 mhys., and its reactance at 100,000 cycles 5·8 ohms. It therefore requires a capacity of about 0·3 microfarad to produce resonance.

If the capacity of the aerial which it is required to excite has a lower value than 0·3 mfd., it must be connected to the alternator through an air-core transformer or jigger of appropriate turns ratio, which will be determined by the capacity and effective resistance of the aerial, and the scheme of connections will be as shown in Fig. 58.

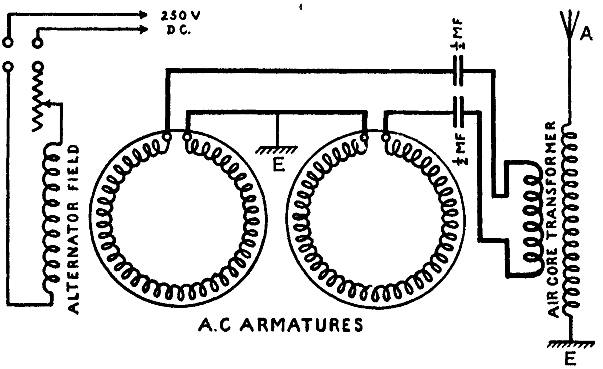


FIG. 58.—The Alexanderson 100,000-cycle Alternator: Scheme of Alternator—Aerial Connections.

Under such conditions, with air gaps of 15 mils, an output of 2 kw. at 150 volts can be obtained. As the input of the driving motor is then about 12 kw., the over-all efficiency is about 17 per cent.

When output depends very much on resonance, it is clear that the maintenance of a constant rotor speed is of primary importance. Under working conditions the rotor acts like a fly-wheel, and its own energy of motion tends to maintain the frequency constant when the load is applied; but for the safety of the set it is essential that the necessity for sending much energy back through the gearing should be avoided, and the driving motor is therefore fitted with automatic controls which ensure that it runs at unvarying speed.

A further precaution is to keep the load on the alternator constant; that is, the transmission of signals should be effected by transferring the load, by means of the signalling key, alternately from the aerial to a dummy circuit having the same electrical constants as the aerial. This method of working, of course, still further reduces the over-all efficiency of the set—the ratio of useful power in the aerial to input.

Alternators of 200,000 cycles have also been constructed on a similar principle to the one described, but the spacing of the armature conductors relative to the inductor spokes is different, being as shown in Fig. 59, and the number of spokes is 800.

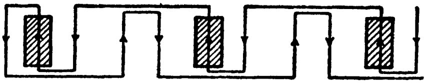


FIG. 59.—Alexanderson 200,000-cycle Alternator: Relation of Armature Winding to Stator Spokes.

H.F. Alternator of the Société Française Radio-Electrique.—Fig. 60 illustrates a 25-kw. alternator which has a frequency of 30,000 cycles at a rotor speed of 6000 r.p.m.

It consists of a stator, S, (Fig. 60 (*a*)), having a central, cylindrically wound, exciter winding, H; and a single zigzag armature winding, Z, in slots on its inside surface. The rotor consists of a heavy fly-wheel type of steel disc, R, with a wide periphery fitted with two sets of teeth mounted cylindrically, so as to face the armature winding on the stator.

The flux passes from the part of the stator A, (Fig. 60 (*b*)), to the teeth on the rotor, B, thence along the rotor to the teeth C, and returns to the stator, cutting the same armature coils at D.

In order that the E.M.F. induced in the stator winding by the variation in the flux caused by the travelling teeth B, shall be in the same direction as the E.M.F. induced by the varying flux caused by the teeth C, the teeth C are displaced

180 electrical degrees relative to the teeth B (see Fig. 60 (*c*)). The frequency is determined by the product of the number of teeth in one of these sets B, or C, into the revolutions of the rotor, each tooth and space corresponding to a pair of poles in a standard alternator. There are 324 teeth in each set, and the length of each polar tooth is about 4 cm., and the width ·36 cm.; width of slot ·38 cm.; maximum depth ·38 cm.

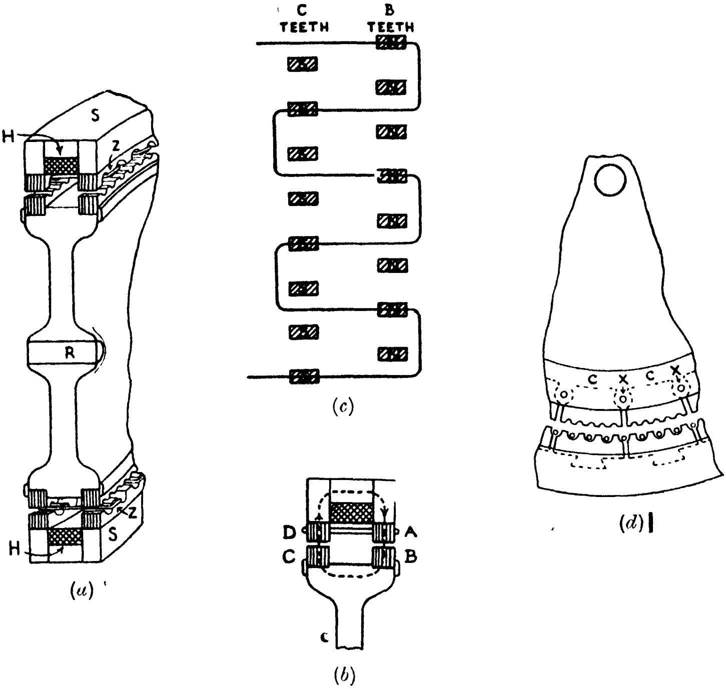


FIG. 60.—H.F. Alternator of the Société Française Radio-Electrique. 25 kw. 30,000 Cycles.

They are made up of stampings of soft iron, said to contain some silica, each having a thickness of ·05 mm. Stove enamelled stampings alternate with all-bright stampings when they are assembled together. Each stamping enters into the construction of six polar teeth, and is cambered accordingly. Each group of stampings has end-plates of brass of the same shape, but of one millimetre in thickness, and is dovetailed in a slot in the periphery of the rotor (see Fig. 60 (*d*)).

The 54 polar groups are then gripped in position by means of a steel clamping ring, C (Fig. 60 (*d*)), shaped so that it partly enters the slots, and bears on the brass end-plates—the ring being riveted through at X to a similar ring on the opposite face of the rotor holding the second set of polar teeth in place.

The stator stampings have fewer and wider slots than the rotor. The arrangement allows larger section copper to be employed, less inductance in the armature winding, and therefore more current and higher power. There are two slots on the stator to three teeth on the rotor. If a rotor and stator stamping are put opposite each other, as shown in Fig. 60 (*d*), it will be seen that when the centre of the first stator slot which carries the conductor is opposite the centre of a rotor tooth, the centre of the next stator slot carrying the wind-back of the zigzag conductor is opposite the centre of a rotor space, and so on. The creation of eddy currents in the polar teeth is thereby discouraged.

Each group of alternate bright and enamelled stator stampings is mounted in its dovetailed slot, and there are two sets of such slots, one on each side of the cylindrical exciter coil; and they are in line, and not staggered like the two sets of rotor stampings.

The 54 groups in each set are mounted in a number of stator yokes, which can be moved in towards the rotor, thereby providing air-gap adjustment. The stator winding consists of a single zigzag of stranded enamelled copper, covered with paraffin-waxed cotton, and laid in Bakelite tube.

The Goldschmidt Alternator.—In any alternator of standard design, such as is shown in Fig. 52 (*a*) or (*b*), if a direct current is passed through the windings on its poles so as to produce a constant magnetic field, and the armature is rotated in this field, then an alternating E.M.F. will be produced in the armature winding having a frequency *n*, which is given by the product of the number of pairs of poles and the number of revolutions of the armature per second.

Now the current which flows through the armature winding when the circuit is completed is accompanied by its own magnetic field, which is equally capable of reacting on any windings cut by it, such as the pole windings.

If the armature current were constant, its field would be constant, and the E.M.F. induced in the pole windings would also have a frequency *n*, as the frequency is determined by the product of the number of armature coils and the number of revolutions of the armature per second.

But the armature current and its field are not constant, they vary with a frequency *n*, and this variation has a twofold effect when considered in its inductive relation to the pole coils, which can be better understood if we consider the pole coils as being made up of active conductors parallel to the armature conductors, joined together by end connections. If the armature circuit is tuned to resonance by a suitable condenser, the current will be in phase with the E.M.F., and it will reach its maximum when the conductors are opposite the pole centres.

A field which is increasing in strength, and is at the same time approaching a conductor is equivalent to a steady field in movement which has a rate of change, relative to the conductor, of *n*, the electrical frequency, plus *n*, the mechanical frequency, $= 2n$.

Also a field which is leaving a conductor, and is at the same time decreasing, has a rate of change relative to the conductor equal to the sum of the mechanical and electrical frequencies, which in this case $= 2n$.

But while the armature field is approaching one pole conductor it is at the same time leaving another, and it is obvious that the inductive effects on both conductors must be considered, particularly when they are close together, and still more so if the frequency of the armature current is a multiple of the original frequency induced by rotation in the D.C. field.

The effect of increasing the strength of the magnetic field as it moves away from a conductor is to lessen the rate of change relative to the conductor; that is, the rate of change becomes *n*, the electrical frequency, minus *n*, the mechanical frequency, which in this case equals 0, the tendency therefore being to produce a field of constant strength acting on the lagging coil; and it also follows that a field which is decreasing in strength as it approaches a coil generates an E.M.F. in the coil having a rate of change *n*, the electrical frequency, minus *n*, the mechanical frequency, = 0.

Then the total result of this first reactive induction of a half cycle of armature current acting on the pole conductors of each coil, is to produce in the leading conductor during the rise of the current, and in the lagging conductor during the fall, an E.M.F. having a frequency twice that of the armature current.

But the pole windings of the standard alternator are not designed to encourage currents resulting from induced E.M.F.'s of this nature. In the first place they are usually wound with many turns of fine wire and their inductance is extremely large, so that even if the losses of transformation were small, the resulting current could not be otherwise than extremely small.

In the next place the windings are usually well screened from the full influence of the armature and field by the projection of the pole shoes. Again, much of the energy of the varying field is wasted in hysteresis in the pole iron, and still more in eddy currents in the pole faces.

The high-frequency alternator of Rudolf Goldschmidt, which makes use of the effect just described, is therefore constructed in a manner which tends to eliminate as far as possible all these adverse conditions.

The stator D.C. field winding is similar to the rotor armature winding and has the same inductance. It is also exposed on the pole face of the stator to the full effect of the rotor field (see Fig. 61).

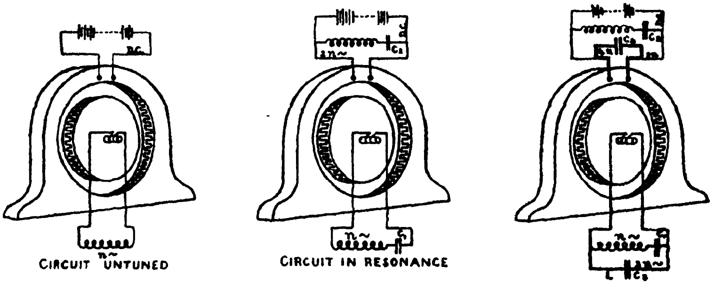
Both rotor and stator cores are made up of very finely laminated iron, 30 per cent of the total bulk of the cores being due to paper separators between the laminations.

The current of frequency $2n$ induced in the stator winding is encouraged to the utmost by shunting the D.C. supply with a suitable condenser, C_2 (see Fig. 61 (*b*)), so chosen that this condenser and the stator winding constitute a circuit which resonates at the $2n$ frequency. Thus a current generated in the armature having a frequency of 10,000 cycles per second may induce a current having a frequency of 20,000 cycles per second in the stator.

But this frequency is still much below what is required to excite an average aerial.

The application of the principle on which this alternator works is, however, capable of further extension, provided the losses in each transformation of frequency are not too great.

Thus the current of frequency $2n$ in the stator is accompanied by its own magnetic field, which, through its cyclic variation combined with the relative motion of rotor and stator, is able to induce two E.M.F.'s in the rotor winding, one of which has a rate of change given by the *sum* of the frequency of the inducing current $2n$ and the rotational frequency $n = 3n$, and the other a rate of change given by the *difference* of the inducing current and rotational frequencies, namely, $2n - n = n$.



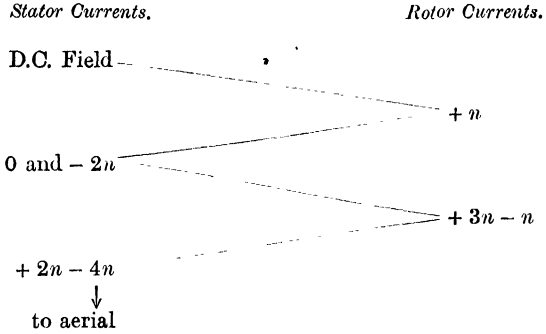
(*a*) (*b*) (*c*)

FIG. 61.—The Goldschmidt H.F. Alternator.

Further, a current at the higher frequency $3n$ can be developed to its maximum by adding a suitable condenser, C_3, to the rotor circuit (see Fig. 61 (*c*)), such that the inductive path L, C_3 resonates at this frequency; while, if the losses due to this second transformation are kept very low, the E.M.F. of the lower frequency n induced in the rotor winding will practically wipe out the original rotor current of frequency n, as it will lag almost 180° of phase behind the original E.M.F. generated by the rotation of the armature winding in the D.C. field, and will almost equal it in amplitude.

This process can be again repeated, the rotor current of $3n$ inducing a resultant E.M.F. of a frequency $4n$ in the stator, while the stator in its turn must be provided with a branch circuit having a natural period $4n$, and so on. But the present practical limit of transformation is reached with the production of a current of $4n$ frequency in the stator, which is made to feed direct into the aerial as its resonant circuit.

The various stages in the growth of the frequency are therefore as follows:—



and the resultant active currents are the D.C. field current and the aerial current in the stator, and a current of frequency $3n$ in the rotor.

The phase relationships of the various induced frequencies as indicated by the signs + and − can be obtained from a consideration of the ordinary principles of induction.

Thus, in a static transformer the field produced by the primary current is common to both windings, and the E.M.F. it induces in the secondary is in phase with the back E.M.F. it induces in the primary, and if there were no other E.M.F.'s to consider, currents would result in the windings which were in phase with each other, but opposite in phase to the original primary current; so also in a rotary transformer of the Goldschmidt type, the primary current of frequency $+n$ induces a secondary current of $-2n$, and also as a result of the back E.M.F. a current of $-n$ in the primary, which completes the first operation.

In the second operation, the primary current of $-2n$

induces a secondary current of $+3n$, and also a back E.M.F. resulting in a current of $+2n$ in the primary, and so on. At each successive step, the losses increase, as in practice the currents of intermediate frequencies do not absolutely wipe out; there is the complication of an additional tuning circuit; and, finally, the necessity of maintaining the speed of the rotor constant becomes of increasing importance. For the output depends to a very great extent on the establishment of a condition of resonance between the induced currents and the fixed circuits provided for them, but a variation in the original frequency n of the machine; due to a change in speed of the rotor, must be multiplied by the number of transformations to obtain the variation in the final frequency, so that even the very smallest change in speed has a big effect in curtailing the output and must be prevented.

The alternator at the Hanover Station has a single conductor zigzag winding, forming 384 poles on both stator and rotor. The rotor runs at a speed of 3130 r.p.m. and at this speed generates 10,000 cycles, which is transformed in three steps to 40,000 cycles (7500 metres wave-length). The power delivered to the aerial is stated to be 160 kw. with a current of 200 amperes. The rotor of the alternator at the Tuckerton Station, U.S.A., has 300 poles, is 3 ft. in diameter, and therefore has a spacing of ·377″ between centres of conductors. It runs at 4000 r.p.m., which gives it a peripheral speed of 192 metres per second. The air-gap is less than 1 mm. There are three steps of frequency transformation, from 10,000 cycles to 40,000 cycles. The power delivered to the aerial is given as 117 kw. with 140 amperes flowing, and the efficiency of the alternator on a long dash, from D.C. input to aerial output, as 54 per cent.

The scheme of connections so far as it concerns the alternator is as shown in Fig. 62. The field of the stator is first excited by closing the operating key, K, in the battery circuit. The current of frequency $n = 10,000$ cycles, thereby generated in the rotor, flows through the resonating circuit L_R, L_1, C_1. As, at the frequency $n = 10,000$ cycles, the reactance of the shunt circuit C_8 is very large compared with the path L_1, C_1, practically no current at this frequency flows through C_3. The current at 10,000 cycles in the rotor induces a current of $2n = 20,000$ cycles in the stator, which flows through the circuit adjusted to resonate at this frequency, namely, L_S, L_2, C_2, but is prevented from flowing through the D.C. exciting circuit by the choking coils L_X and L_{XA}, or into the aerial-earth-condenser circuit C_4 by reason of the high reactance of this path.

The current at 20,000 cycles in the stator induces a current having a frequency $3n = 30,000$ cycles in the rotor, which has for its tuned circuit the path L_R, C_3, the shunt L_1, C_1 having a high reactance for currents of this frequency.

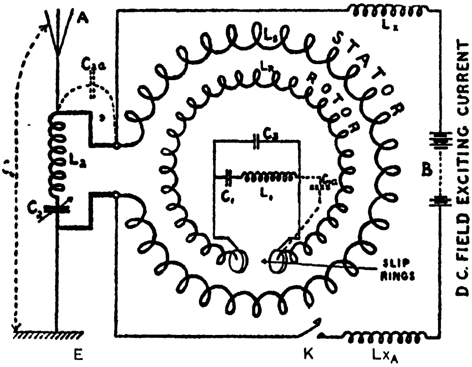


FIG. 62.—The Goldschmidt H.F. Alternator: Scheme of Alternator—Aerial Connections.

The 30,000 cycle rotor current creates a current of $4n = 40,000$ cycles in the stator winding, which has provided for it the in-tune circuit made up by the aerial, L_S, and earth; while the shunt circuits L_2, C_2, and L_X, B, L_{XA}, have both too high a reactance to divert much of the 40,000 cycles energy through them.

The additional condensers C_{1a} and C_{2a} come into use in place of the plain conductors when the speed of the rotor is increased so much that n, the original frequency, is of the order 15,000 cycles instead of 10,000 cycles, and the final frequency 60,000 cycles instead of 40,000 cycles.

In order to maintain a constant rotor speed, the tendency of the driving motor to slow down when the load is applied is counteracted by a relay action—not shown in the diagram—of the operating key K, which, at the moment of closing the alternator field circuit, also increases the independent field current of the motor, so that the machine is at the same time subjected to a tendency to speed up.

Static Frequency Changers.—There are several methods available for doubling or tripling the frequency of an alternating current, which can be used in conjunction with a high-frequency alternator. Two of the simplest of these, which depend for their operation on the form of the magnetisation curve of iron, will now be described.

It is well known that the strength of the magnetic field B, created in a piece of iron, is not directly proportional to the magnetic force H, as represented by the ampere turns of the magnetising winding.

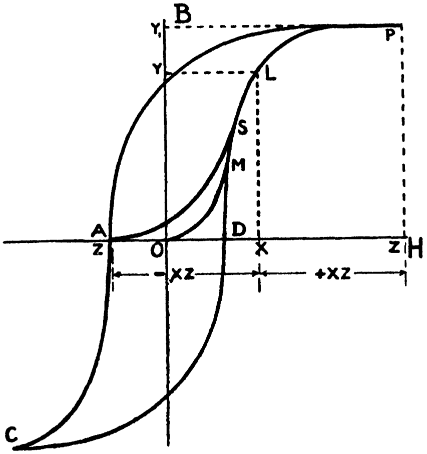


Fig. 63.—Static Frequency Changers: the Magnetisation Effects in Iron of Direct and Alternating Currents, I.

Starting with a completely unmagnetised bar of iron, we obtain an HB curve as shown by OMLP (Fig. 63). If, on reaching the point P, the current producing the magnetising force H is diminished, the rate of fall of the induction will be slower than its previous rate of increase, and if H is reversed and increased until an equal value of induction, B, is obtained in the opposite direction, the HB curve will take the shape PAC in the same figure.

A further fall of current, followed by reversal and increase to the amount we started with, will complete the cycle of change and give us the loop curve PACDP. The curve shows that the magnetisation lags behind the magnetising force, which effect is termed *hysteresis.*

Let us provide the iron with two independent windings, and through one of them let us send a direct current of such a value that the magnetising force, OX, produces an induction OY, at L, on the knee of the curve, and through the other let us send an alternating current which will produce a magnetising force having a maximum value XZ.

Then when the alternating current assists the direct current, the magnetising force $H = OX + XZ$, and the *change* of induction is given by the small quantity $OY_1 - OY = Y_1Y$; but when the alternating current opposes the direct current the magnetising force $H = OX - XZ$, and the *change* of induction is $OY - 0 = OY$. The hysteresis loop for the complete cycle of magnetisation due to the cycle of alternating current is ASLPA.

This unequal induction effect explains the curves in Fig. 64, where Ot is the time axis, OI_X represents the value of direct current, and OI_Z the maximum value of the alternating current; while on the corresponding flux curve OY represents the induction due to the direct current OI_X, and YY_1 the increment due to the addition of the alternating current OI_Z, the induction falling to zero when the two currents oppose.

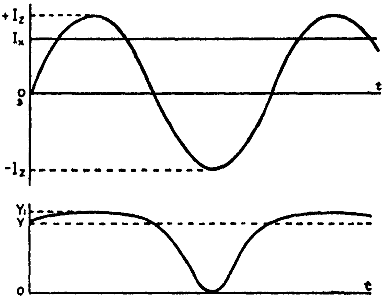


FIG. 64.—Static Frequency Changers: the Magnetisation Effects in Iron of Direct and Alternating Currents, II.

Vallauri and M. Joly have applied this principle to produce a current having double the frequency of the supply, in the following manner:—

Two similar transformers, A and B (Fig. 65), having three windings, are connected with their primaries, PP, in series to the A.C. supply, their secondaries, SS, in series to the tuned double-frequency load circuit LC, and their tertiaries, TT, in series through a large choking coil, X, to the D.C. supply. It will be seen that when the D.C. field assists the A.C. field in one transformer, it opposes it in the other, and *vice versa.*

Then if the flux curve (*b*) (Fig. 66) represents the change in field strength in the core of transformer A, corresponding to a variation of A.C. current (*a*), the flux curve (*c*) represents what will occur in the core of transformer B, under the influence of the same current.

The secondary windings, SS, convey the effects of both these flux changes to the one circuit. The resultant flux change affecting this circuit is shown by the heavy line curve in (*d*), obtained by superposing curves (*b*) and (*c*), and the E.M.F. induced in it in consequence, by the curve (*e*), which is seen to have double the frequency of the A.C. supply, (*a*). The choke X is to prevent current of frequency $2n$ being generated in the D.C. circuit.

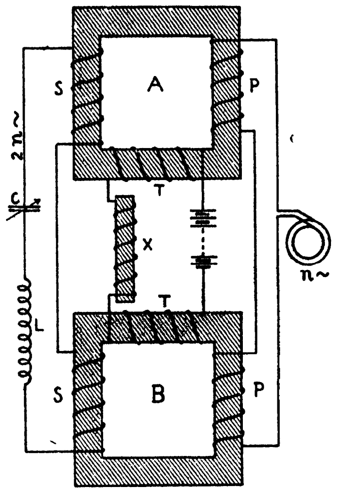


FIG. 65.—The Double - Frequency Changer of Vallauri and M. Joly: Transformer Connections.

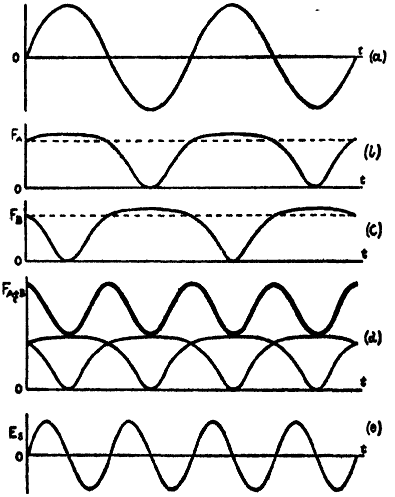


FIG. 66.—The Double-Frequency Changer of Vallauri and M. Joly: Current, Flux, and Potential Curves.

M. Joly's arrangement for tripling the frequency of supply is as follows:—

Transformer A (Fig. 67) is fitted with three windings—a primary, which receives the A.C. supply; a secondary, which delivers the load current; and a tertiary, which is used, as before, to saturate the core by means of a D.C. current. Transformer B is of standard type, having two windings and an unsaturated core.

The two primaries are connected in series, and the two secondaries in series, but so that the induced voltages oppose each other.

Under these conditions the build-up of the triple frequency is illustrated in Fig. 68, where curve (*a*) represents the supply current, curve (*b*) the change of flux in transformer A, curve (*c*) the induced E.M.F. in the secondary of A as a result of (*b*), curve (*d*) the secondary E.M.F. in the unsaturated transformer B, and the heavy curve (*e*) the resultant E.M.F. of triple frequency in the load circuit due to the difference of the secondary E.M.F.'s of transformers A and B.

Static methods for producing high-frequency currents involve, as with rotational methods, losses from eddy currents and hysteresis, but as considerations of mechanical strength do not now enter into the design to nearly the same extent, it is possible to keep down such losses to the very lowest limits.

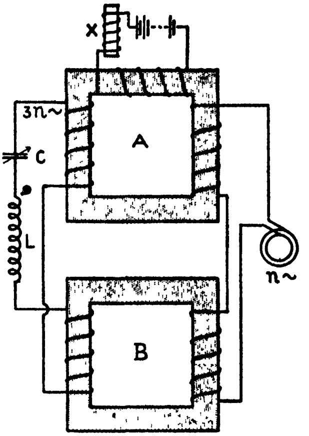


FIG. 67.—The Triple-Frequency Changer of M. Joly: Transformer Connections.

Continuous Oscillations by the Marconi "Timed-Spark" Method.—If we have a source of high-tension direct current, and a high-frequency primary circuit which includes a Marconi disc discharger, we can produce continuous oscillations in the coupled secondary, or aerial circuit, in very much the same way as a pendulum is kept swinging—by impulsing the aerial at the correct moment by a dead-beat discharge in the primary, once every complete cycle of natural oscillation of the aerial.

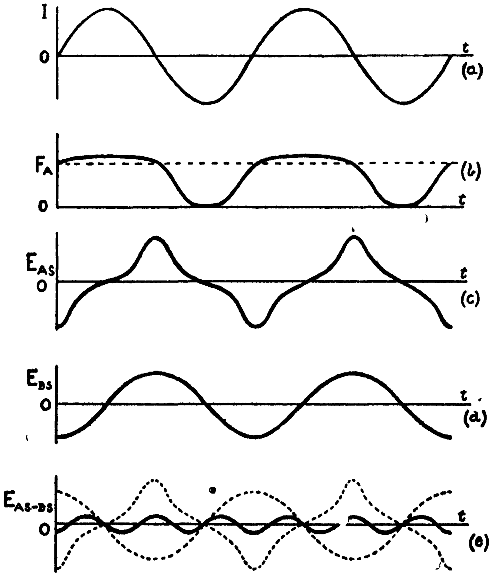


FIG. 68.—The Triple-Frequency Changer of M. Joly: Current, Flux, and Potential Curves.

But for this to

be possible the disc must run at extremely high speed, it must have a large number of studs, and the discharge must be very accurately timed. Even then it will only be possible to obtain a maximum frequency of discharge suitable for a very long wave-length —although such a frequency would be high enough to place a decided limit on the power that a single disc could deal with. A more practical arrangement, although somewhat more complex in character—which has, for several years now, stood the test of the severest working conditions for long periods on high power, and on which a British Government Commission in 1913 reported more favourably than on any other long-distance continuous wave system then in use—is described in principle below:—

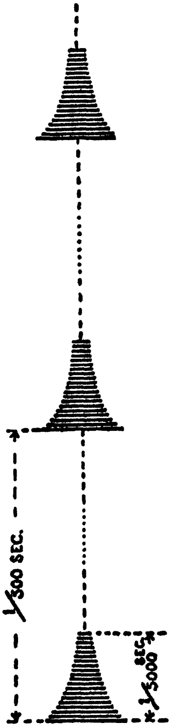


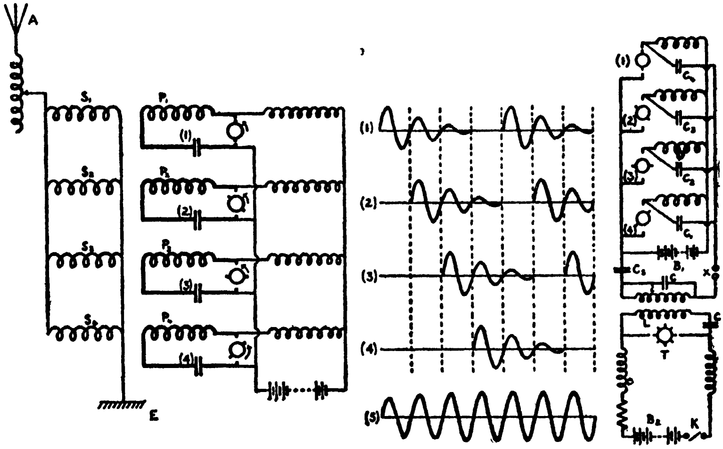
FIG. 69.—The Relation of Sparking Period to Non-Sparking Period for a Synchronous Spark Discharge.

The ordinary spark discharge consists of a number of trains of high-frequency oscillations which succeed each other at regular intervals, but each train dies out very quickly, or is abruptly cut short by the rotation of the disc, leaving a comparatively long period during which no energy is given to the aerial at all. Fig. 69 illustrates the case of an alternator supply of 250 cycles, a synchronous spark frequency of 500 per second, an oscillation frequency of 100,000 per second corresponding to a wave-length of 3000 metres, and a wave-train of 20 oscillations. The ratio of the non-sparking to the sparking interval is then 9 : 1. But suppose the arrangement of circuits is such that the aerial can be energised from a second source during the time the first source is not working, and further, from a third source when neither the first nor second sources are working, and, if necessary, from a fourth source, etc.; it is conceivable that in this way the aerial can be given a continuous supply of oscillatory energy; that is, we can obtain this result by using a number of independent circuits producing damped trains of oscillations, which act inductively on the aerial in timed sequence.

But in order that the amplitude of the aerial oscillations should be constant, the trains of oscillations in the various sources of supply *must overlap and be in phase.*

In Fig. 70 (*a*), four similar H.F. circuits are shown, numbered 1, 2, 3, and 4 respectively, the condensers of which are charged in parallel from a source of high-tension direct current—in this case an accumulator battery.

The four disc dischargers are mounted in an insulating manner on the same shaft, and therefore run synchronously, but the relation of the electrodes to the disc studs is different in each circuit, being such that the condensers do not discharge together but at equal intervals apart. Each circuit acts inductively by means of a coil P, on a coil S, forming part of the aerial circuit, so that the total effect on the aerial is somewhat similar to that of a single circuit working at four times the frequency of charge and discharge, but it differs in the following respect. When the discs are revolving slowly, first the train of oscillations started by discharger (1) takes place, then the train due to the discharge in circuit (2), followed at set intervals by the discharges in circuit (3) and in circuit (4).



(*a*) (*b*) (*c*)

FIG. 70.—The Marconi "Timed-Spark" Method of producing Continuous Oscillations.

As the discs increase in speed, the intervals between the series of oscillations decrease, and the trains close up, but the time from start to finish of each train will in general remain unaffected, as it is short compared with the time the studs take to pass the electrodes. In the exceptional case when the oscillation wave-length is very long, the peripheral speed of the disc very high, and the widths of the studs and electrodes comparatively narrow, the oscillations may be quenched while there is still much energy in the train.

If the discs continue to accelerate, the trains will commence to overlap, and finally a speed will be reached at which they overlap in phase, and on so many oscillations that the combined effect is that of a constant amplitude, as shown in Fig. 70 (*b*).

The relative timing of the discharges is of great importance. It is clear that only a coarse adjustment can be obtained by rocking the disc electrodes in the four circuits, so many angular degrees lag, or lead, relative to a given position of the disc studs. Electrical timing by means of a *trigger spark* is therefore also employed, the principle of which is illustrated in Fig. 70 (*c*).

In this diagram the main oscillatory circuits are not shown.

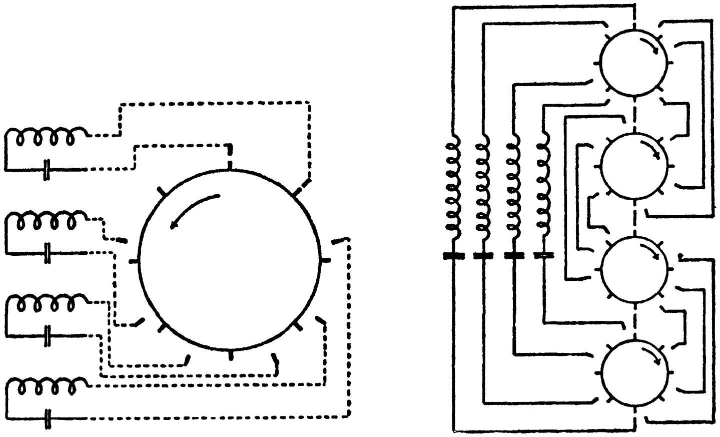
The potential applied by the main battery, B_1, to any of the main discs, is of such a value that a spark will not pass across the two air-gaps—even when the rotation of the discs brings the studs and electrodes to their nearest position—until the breakdown pressure is augmented by the extra potential supplied by the trigger circuit.

An oscillatory circuit LC, provided with a disc discharger T, is fed from a high-tension direct current supply B_2, and energises a secondary circuit, *l*, *c*, which is tuned to it.

The "trigger disc," T, is mounted on the same shaft as the four main discs, but it has four times as many studs, so that whenever any of the studs on any of the main discs come in line with their respective electrodes the trigger disc will be in a position for sparking.

The circuit *l*,*c*, provides the potential for the trigger sparks in the branch circuits X, C_1, (4), C_s; X, C_2, (3), C_s; X, C_3, (2), C_s; X, C_4, (1), C_s; which is encouraged to mount to a high resonance value before discharge by the insertion of the plain spark-gap X. The condensers C_1, C_2, C_3, C_4, C_5, tune the branch circuits to the trigger wave-length, but mis-tune them to the wave-length of the main high-frequency circuits.

When the high-tension operating key, K, is working, a high-frequency spark takes place at T, which is followed by a resonance discharge spark at X, in series with main disc sparks at whichever discharger has its studs in line with the electrodes at that moment. This action triggers the main discharge, which has a somewhat lower frequency.



(*a*) One Disc used with four Discharge Circuits.

(*b*) Four Discs in Series in each Discharge Circuit.

FIG. 71.—The Marconi "Timed-Spark" Method.

Fig. 71 (*a*) shows a variation of the main circuit connections, in which one disc discharger can be used instead of four, the necessary condition being that the diameter of the discharger is such that the spacing of the studs allows the electrodes connecting to the different circuits to be fitted at the requisite angular distances round the periphery, without danger of spark-over from one circuit to another.

The connections of the trigger circuit in Fig. 70 are such as to include both the air-gaps at each main disc. It is found sufficient in practice if the trigger spark is arranged to lower the resistance of only part of the total air-gap, the main battery potential being then sufficient to break down the remaining part.

Particularly would this be the case were a number of main discs to be used in series, as shown in Fig. 71 (*b*), in order to deal with a high voltage. It would be necessary to trigger only one of them in each circuit.

Continuous-Wave Arc Transmitter.—Although previous experimenters had used similar circuits, W. Duddell, in the year 1900, was the first to show conclusively that a short arc in air between solid carbon electrodes, when fed from a source of constant E.M.F., and having a suitable condenser and inductance connected in parallel with it, was able to give out a musical note, the audible frequency of which was the same as the oscillation frequency of the in-parallel electrical circuit. Within a certain range of frequency, the Duddell arc was able to produce continuous electrical oscillations.

A general explanation of this effect may be stated as follows:—

Under the conditions which obtain when continuous oscillations are produced, the arc characteristic—that is, the curve showing the relation of the current through the arc to the potential maintaining it at the electrodes—is similar to the operating characteristic of a circuit containing a condenser: they are both *falling characteristics.*

As the arc current increases, its effective resistance falls, and the potential required to maintain it falls; and when a condenser discharges, the current grows as the potential behind it falls.

When the arc current decreases, its effective resistance increases and the arc potential rises; also when a condenser is being charged, the current falls as the current potential increases.

Now the effect of connecting an oscillatory circuit to an arc is to make it unstable. The condenser commences to charge and takes current from the arc. This alters the arc resistance, and the arc potential rises a small amount, which adds another small charge to the condenser, and this process continues until the condenser potential reaches the same value as that of the supply. But it does not stop here, it receives a further charge from the lagging current in the inductance in series with it, so that finally the condenser potential rises above that of the arc.

This condition tends to start a surge of current back from the condenser through the arc; the condenser potential then falls, and the arc current grows, but as it grows it lowers the arc potential below that of the condenser; and this process in its turn continues, being assisted by the inductance, until the over-discharge of the condenser equals the previous overcharge, when again a reversal takes place, and so the oscillation is maintained.

The arc and condenser characteristics are not by any means identical; in fact, as shown above, a difference is necessary in order to start a circulating current.

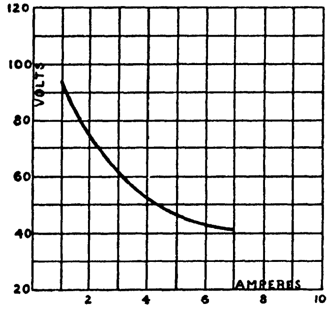


FIG. 72.—The "Static Characteristic" of an Arc.

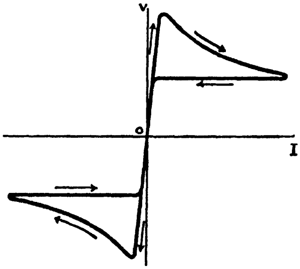


FIG. 73.—The "Dynamic Characteristic" of an Arc.

Fig. 72 shows the direct current, or *static characteristic*, Fig. 73 the alternating current, or *dynamic characteristic*, of an arc, and it will be observed in this last case that the arc potential for a rising current is higher than for a falling current.

This effect is due to the change in the arc resistance lagging behind the change in the potential applied to the arc —for conductivity depends on the numbers of gaseous ions produced by the potential and incandescence of the electrodes, and therefore must lag by an amount which is determined to a considerable extent by the mobility, or rate of movement, of these ions. Again, when once they are produced, the ions must take a definite time either to transfer their charges and become neutral, or else to dissipate themselves in the space outside the flame of the arc.

The character of the Duddell arc current is that of an oscillatory current of amplitude I_2 (Fig. 74) superposed on a direct current of value I_1, with the result that the arc current varies between the values $(I_1 - I_2)$ and $(I_1 + I_2)$.

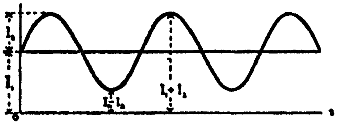


FIG. 74.—The Duddell Arc Current.

These values are marked on the static characteristic AB of Fig. 75, and the heavy line loop curve shows the dynamic characteristic when the current oscillates between them.

The maximum frequency to which the Duddell arc will respond, and its efficiency as a generator of continuous waves, are both too low for the commercial requirements of radio-telegraphy. Experimentally, weak currents of 100,000 cycles and even 400,000 cycles have been obtained, but the practical working limit is very much below these values.

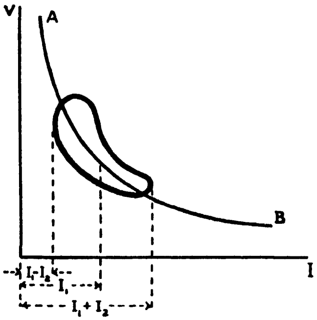


FIG. 75.—The Duddell Arc: its Static and Dynamic Characteristics.

In the first place, the lag of arc current behind potential, as indicated by the area of the loop characteristic, is very pronounced for air, and it is this lag which determines the maximum frequency of the arc oscillations, for clearly the arc cannot take up oscillations having a period less than its own time lag.

In the second place, the efficiency of the arc must depend greatly on the extent to which the energy of the direct current is converted into the oscillatory energy of the condenser current, and the best arrangement is therefore more likely to be arrived at when, instead of the oscillatory current occurring as a simple ripple on the arc current, its amplitude is so great that $(I_1 - I_2) = 0$; that is when it is able to neutralise or quench the arc current in the trough of each oscillation.

If the supply voltage is kept constant, the oscillatory current will be increased if the capacity of the condenser is increased. But this leads to increased heating of the electrodes, and a consequently greater ionisation of the gap, which renders the arc current less responsive to changes of potential—the arc will have to work on the lower and less sensitive part of its static characteristic,—so that a limit is soon reached, above which it is inadvisable to increase the condenser capacity.

An important advance was therefore made in the utility of the arc circuit when, in 1903, V. Poulsen introduced certain improvements which had the effect of—

(*a*) Increasing the steepness of the static characteristic, so that for the same change of arc current a larger charging voltage was applied to the condenser;

(*b*) Reducing the area of the dynamic characteristic, so that it became possible to use the arc with oscillatory circuits of higher frequencies;

(*c*) Quenching the arc each oscillation, which, together with (*a*), increased its power capacity.

These improvements were:

(1) The use of a hydrogenous atmosphere for the arc instead of air. The greater ionic mobility of hydrogen increases the rate of de-ionisation of the gap as the potential falls, and consequently extends the working range of frequency upwards. A comparison of the static characteristics of air and hydrogen arcs is shown in Fig. 76.[1] As hydrogen does not attack the arc electrodes, the latter heat up less, and therefore can deal with more power. Coal gas, or alcohol, is very often used instead of pure hydrogen.

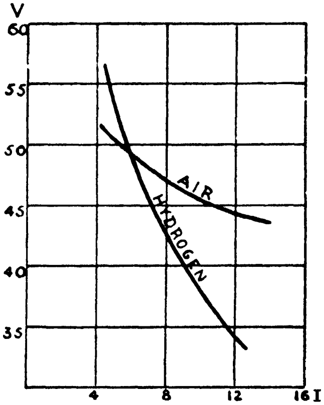


FIG. 76.—Arcs in Air and Hydrogen: Static Characteristics.

(2) The use of a water-cooled copper anode. The anode

---

[1] W. L. Upson, "Observations on the Electric Arc," *Proc. Phys. Soc.*, London, vol. xx., 1907.

particularly tends to heat up and to feed the arc with ions. By using a good heat conductor, such as copper, and water-cooling it, the responsiveness of the arc is improved, its quenching is encouraged, and any tendency to start in the reverse direction after quenching is discouraged.

(3) The use of a transverse magnetic field. By its blow-out effect on the arc, it progressively extends the path followed by the ions until it reaches the breaking point, so that when the arc is quenched the de-ionisation is much more complete, and the rise of potential on the condenser which then occurs is thereby considerably increased.

(4) The slow rotation of the carbon electrode. This improves the regularity of the arc, causing the carbon to burn evenly, and preventing it from overheating at any one point.

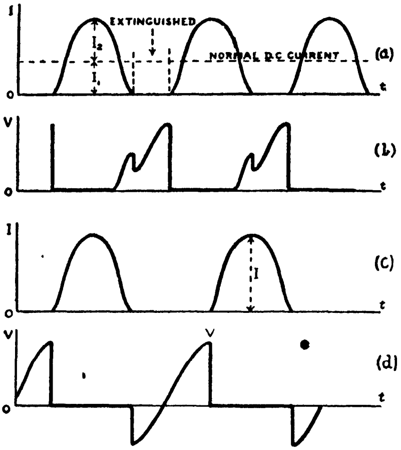


FIG. 77.—The Poulsen Arc: Current and Potential Curves.

It is found that the best results are obtained with the Poulsen arc when I_2 is somewhat greater than I_1, so that there is a definite interval during which there is no arc (Fig. 77 (*a*)). Immediately extinction occurs, the condenser receives a charge from the direct current supply, and the potential rises until ignition again takes place across the almost de-ionised gap, when the cycle of current is again repeated. The best R.M.S. value of I_2 is given by P. O. Pedersen[1] as $\sqrt{2}I_1$. The same investigator shows that the extinction and ignition voltage curve for the very small working gap used in practice has the character shown in Fig. 77 (*b*), whereas a larger gap—causing a higher ignition voltage, V, and greater condenser current, I (Fig. 77 (*d*) and Fig. 77 (*c*)), but resulting in a lower efficiency—will produce a reversal of the arc voltage immediately after extinction. The dynamic characteristic for the small working gap is shown in Fig. 78.

---

[1] *Proceedings of the Inst. of Radio Engineers*, vol. v. No. 4, 1917.

The correct strength of magnetic field depends on the value of the arc current, the frequency of the condenser current, and on the mobility of the gas in the arc chamber.

As the arc does not require to be extinguished so quickly for low-frequency currents as for high, a weaker magnetic field and a less mobile gas can be employed for the former than for the latter.

A field of the correct flux density will allow a single arc to ignite between the near edges of the electrodes, to travel outwards, and to be extinguished once per cycle.

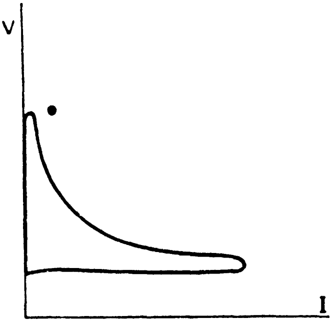


FIG. 78.—The Poulsen Arc: its Dynamic Characteristic under Working Conditions.

A field which is too strong will cause premature extinction of the arc, and will result in a succession of two or more concentric arcs being lit and travelling outwards during each period. The resistance of the arc will be increased and its efficiency lowered.

If the field is too weak, the arc will not quench at the end of each period, but will continue to be blown out further along the electrodes until the potential required to maintain it is sufficient to strike another arc across the shortest gap, when the first arc will be robbed of its current and will quench, and the same process will be again repeated. One arc only will be in existence at any one time, it will quench at irregular times, and may cause the anode or the cathode support to melt. Such an arc is not constant, and its efficiency is also low.

Fig. 79 is a diagram of the Poulsen arc, the water-cooling of the anode not being shown.

The electrodes are connected in series through two high-frequency chokes X, X, with the two field windings M_1, M_2, and an adjustable resistance R, to the direct-current main supply D.

The aircore chokes X, X—which, however, are not always used—protect the field windings, and the choke effect of the field windings protects the dynamo circuit, from high-frequency surges.

The resistance, R, must be in circuit when the arc is struck. After this operation, if the deflection of the ammeter in the aerial circuit fluctuates, the arc gap is increased or diminished by adjusting the cathode until a constant deflection shows that the arc is burning steadily, and is therefore in a fit condition to deal with more power.

The resistance is then gradually cut out of circuit until full power is obtained.

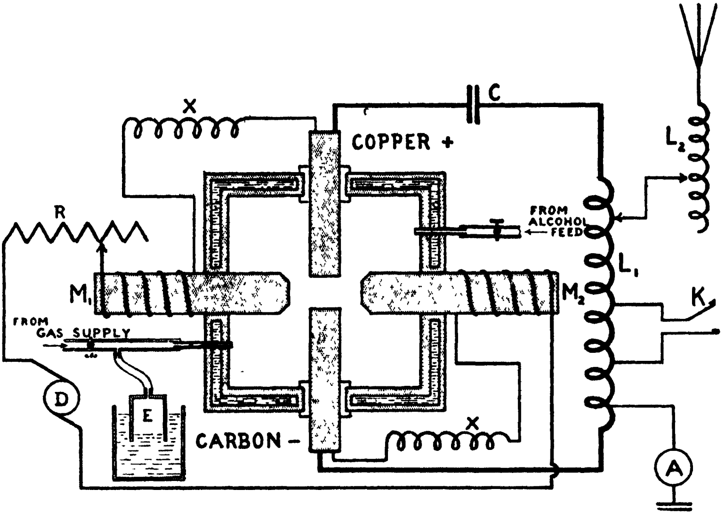


FIG. 79.—The Arc-Aerial Connections of a Poulsen Arc, showing Marconi Expansion Chamber.

The high-frequency primary circuit consists of the condenser C, the inductance coil L_1, and the arc.

The aerial-earth, or secondary circuit, is direct-coupled to the coil L_1 through the inductance coil L_2, which is preferably not part of L_1.

For signalling purposes a mis-tuning device is generally used, as the main supply cannot be interrupted without quenching the arc.

The most usual method employed is to short-circuit one or more turns of the coil, L_1, by means of the operating key, K, when spacing is required between signals, so that the wave-length is altered by 2 or 3 per cent, which is generally considered sufficient to stop the reception of signals on an instrument adjusted to the working wave-length, as with continuous waves sharp tuning is the usual practice.

Alternatively, the operating key switches over to a dummy aerial for spacing purposes.

A Marconi expansion chamber for the arc gases is indicated

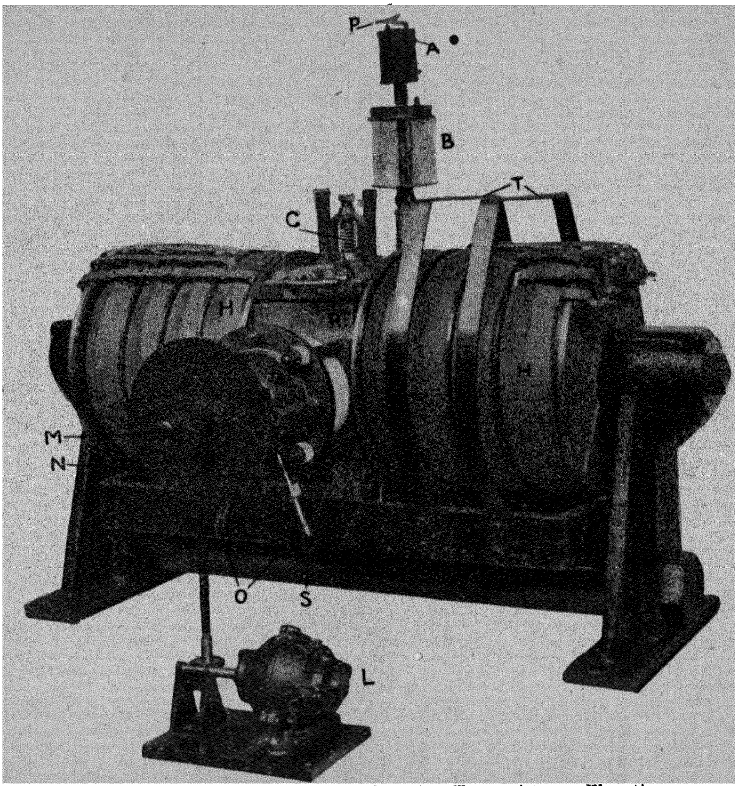


FIG. 80*a*.—A 25-kw. Marconi-Poulsen Arc Transmitter. Elevation.

at E. The use of this fitting in Marconi-Poulsen arcs has been found to have a beneficial effect on the arc stability; to slightly increase the aerial current, and the efficiency; to stop explosions; and to keep the chamber free from soot when either alcohol, coal gas, or petrol is used for the arc atmosphere.

If hydrogen is used, the expansion chamber may be connected by a branch to the supply pipe, but a separate connection to the arc chamber is necessary when alcohol, or any liquid which requires to be vaporised, is employed.

A 25-kw. Marconi-Poulsen Arc Transmitter is shown in Fig. 80*a* and Fig. 80*b*. The various parts are lettered as follows:—A, Plunger solenoid, for distant control of alcohol feed.—B, Alcohol container, showing pressure-equalising pipe. —C, Copper anode.—D, Carbon cathode.—E. Electrode insulator; porcelain.—F, Magnet poles.—G, Relief valve.—H, Magnet coils.—K, Worm-gear drive for rotating cathode. L, Cathode motor.—M, Arc-striking handle. The arc gap is altered by rotating the handle, but to strike the arc it is pressed and then released.—N, Hinged plate which is swung open when it is necessary to remove the cathode.—O, Cathode water-jacket inlet and outlet pipes.—P, Trip control of alcohol feed.—R, Cover water-jacket inlet and outlet pipes.—S, Arc chamber drain-cock.—T, Rest for lid of arc chamber when the chamber is opened. U, Alcohol drip pipe.

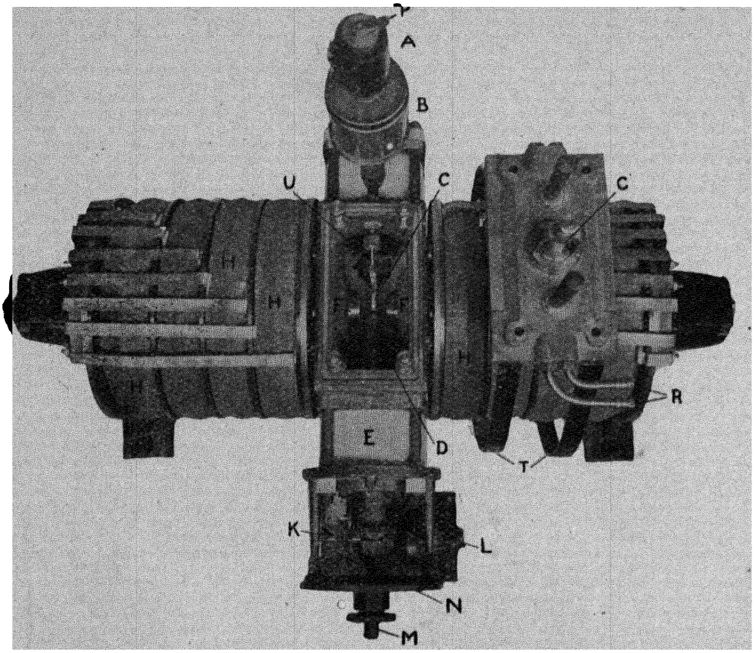


FIG. 80*b*.—A 25-kw. Marconi-Poulsen Arc Transmitter. Plan.

This arc works with a gas pressure equal to about two inches of water.

Its magnet windings are in sections, both for convenience of adjustment for different wave-lengths and to improve the insulation. The outermost sections are connected to the arc electrodes, and as they are therefore more subject to high-frequency surges they are more heavily insulated than the others.

The Valve Oscillator.—In our study of the action of the Poulsen arc we have found that the conducting properties of hot ionised gases can be turned to very profitable account in the generation of continuous oscillations.

In the arc the currents dealt with are comparatively large, necessitating the use as carriers of many gaseous ions of atomic dimensions; but if the currents involved are small, they can be carried by much fewer gas atoms—a semi-vacuum can be used; and further, if high potentials are available, even gas atoms can be dispensed with, and very small currents can be carried through a vacuum by a pure electron discharge alone.

The reactions which take place in vacuum bulbs fitted with suitable electrodes for use in radio circuits will be studied in detail in the next chapter, including the manner in which such bulbs may be used for the production of continuous waves.

CHAPTER V

THERMO-IONIC EFFECTS AND OSCILLATION VALVE PHENOMENA

The Electrical State of Materials at High Temperatures.—The Effect of High Temperature on the Atom.—The Interchange of Electrons between Atoms in a Conductor at High Temperature.—The Oscillation Valve of J. A. Fleming.—Its Rectification Effect.—The Valve Saturation Current.—The Plate Characteristic.—The Effect of increasing the Filament Temperature on the Characteristic.—Method of increasing the Rectification Effect.—The Three-Electrode Valve.—The Control Action of the Grid.—Space Charge.—The Amplification Effect.—Grid-Plate Characteristics.—The Use of different Parts of the Characteristics.—The Effect of altering the Filament Current of the Three-Electrode Valve.—The Filament sometimes connected to the Positive End of the Heating Battery.—The Operation of an Amplifier Circuit.—High-Frequency Amplification.—Low-Frequency Amplification.—The Efficiency of Rectification.—The Retro-Active Effect.—The Reaction Coil.—Simple and Cumulative Rectification.—The Production of Continuous Waves by an Oscillating Valve.—The Effect of a Condenser in Shunt to a D.C. Generator which has a Rippled Wave-Form.—The Reception of Continuous Waves.—The Production of "Beats."—A Valve "Self-Beat," or "Self-Heterodyne" Circuit.—The Oscillating-Valve Telephone Transmitter.—The Use of A.C. Generators for Valve Circuits.—Types of Three-Electrode Valve.—Marconi Valve Instruments.—Receiver, Type No. 27.—Field Station Receiver, Type No. 38a.—Amplifier, Type No. 55.—Multiple Tuner used with Amplifier, Type No. 55.—Multiple Tuner, Magnetic Detector, and Note Amplifier.—Note Amplifier for Use with either Magnetic or Crystal Detector.—Short-Distance Wireless Telephone Transmitter and Receiver.—Short-Distance Wireless Telephone Set, Type T.T. 2.—Wireless Telegraph and Telephone Set, Type T.T. 3.

Thermo-Ionic Effects.—When a metal is heated, at low temperatures it expels gas particles, which are positively charged; at high temperatures, when the metal becomes incandescent, it sends off streams of negatively charged particles—electrons.

This is a preliminary to disintegration, as the gas particles, especially, have assisted—if not by chemical combination, then at least by molecular cohesion—in maintaining the strength of the material.

The number of electrons sent off steadily increases with the temperature until the melting point of the metal is reached.

At high temperatures all solid materials conduct, even those, such as glass and lime, which are insulators at low temperatures. Either they throw off charged gas particles, or clouds of electrons which carry the current.

Many of the oxides are particularly rich in electrons, which they give up on the application of heat.

It has been found that much of the gaseous emission is due to chemical affinity between the gas contained in the hot body and the atmosphere surrounding it, and that it can be very much reduced either (1) by removing the atmosphere,—that is, by heating the material in a vacuum,—or else (2) by using a more chemically inert gas, such as nitrogen or helium, for the atmosphere. The material can then be heated to higher temperatures without melting, the higher temperatures at the same time causing a greater expulsion of electrons.

Now the disturbance created in a gas by heating it is one which increases the translational speed of its molecules, and as the electrons have the nature of an extremely fine-grained gas, we can imagine the actual process which goes on when a solid is heated to incandescence to be that of increasing the translational speed of the secondary electrons along the axes of the atoms, while the movement of the atoms themselves is also increased, but to a very much smaller degree.

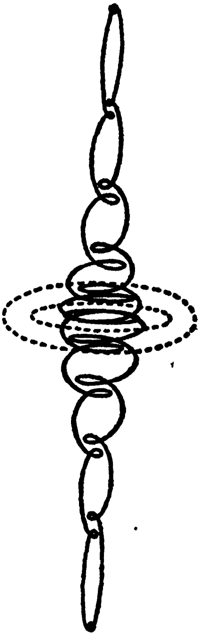


FIG. 81.—The Effect of Increase of Temperature on the Movement of the Secondary Electrons in the Atom.

A rise in temperature may be expected to cause the electrons to spiral in and out of the apertures of the atoms (Fig. 81), and their travel may be made so great that the mutual repulsion of electrons from neighbouring atoms becomes more effective in determining their paths than the atomic pull, so that they disengage entirely from the atoms to which they normally belong, and wander about in temporary freedom, until they come within the effective range of other atoms which have lost electrons—and once more return to captivity. Fig. 82 illustrates such an interchange taking place, and Fig. 83 the effective condition of the filament.

While the electrons are free they are available as current carriers; but, until they are given direction by a suitable E.M.F. applied across the gaseous space, they will not constitute a current, only a charge surrounding the cathode, being held back, although weakly, by the attraction due to the positive charges of the atoms which they have left.

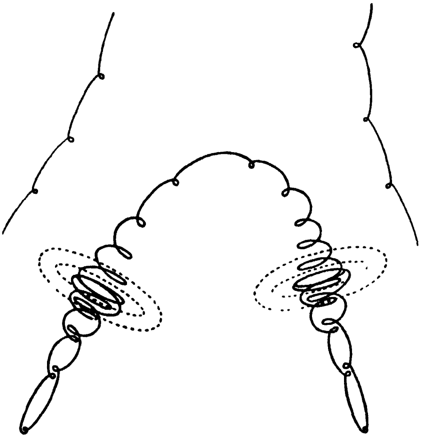


Fig. 82.—Atoms interchanging Secondary Electrons.

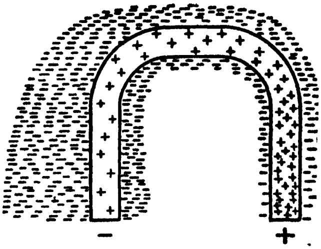


Fig. 83.—The Electrical State of a Glowing Conductor.

The Rectification Effect.—It is clear that the E.M.F. will have most effect when it is such as to draw them away from the hot solid, and least when it should tend to drive them back again to it.

This is the principle of the electric valve action which takes place between two electrodes in a vacuum, when one of them is made to expel electrons, while the other is inactive in this respect.

An E.M.F. which is applied in such a way as to make the hot body a cathode, and the cold body an anode, will drive an electron current through the intervening space, but no current will flow if the cold body is made the cathode.

In the oscillation valve invented by J. A. Fleming in 1904, the cathode, F (Fig. 84), is a carbon or tungsten filament, which is mounted in an exhausted glass bulb, and made incandescent by passing a current through it from the battery, B.

Near it is a cold plate, P, which acts as an anode.

If P and F are now connected to an oscillatory receiver circuit in the shape of an aerial, A, and earth, E, jigger, J, tuning condenser, C, and telephone, T, when the potential induced on P and F by the incoming signals is such as to make P positive and F negative, there will be a tendency for the free electrons surrounding F to be driven towards P, and a valve current will pass; but during the second half of the oscillation, when the potential is reversed—and P is therefore negative—no current will pass between P and F. The telephone thus receives a number of unidirectional current impulses, and the consequent vibration of its diaphragm will give out a musical note if these impulses are split up into groups having a regular and audible frequency.

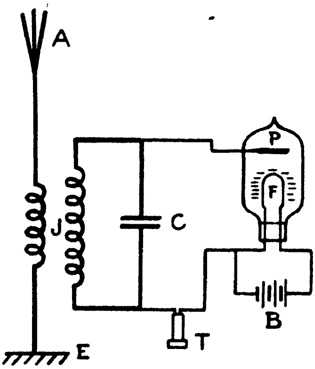


FIG. 84.—The Two-Electrode Valve of J. A. Fleming.

Now the number of electrons which are made available as current carriers by the incandescence of the filament is a quantity which depends solely on the temperature of the filament.

But this does not necessarily correspond to the number which can be made to travel across to the anode as current.

For among themselves the electrons repel each other, and the tendency of those which are furthest from the filament is to drive back those which are newly expelled.

Part of the E.M.F., therefore, which is applied to the electrodes must be expended in driving the electrons carrying the current from the immediate surface of the cathode, against the opposition of the other electrons which they pass on the way to the anode. The current, therefore, for small anode or "plate" potentials is also small.

But as the anode potential is increased, the semi-free electrons surrounding the filament will be drawn on to an increasing extent to act as current carriers, and there will be fewer electrons remaining in consequence to offer opposition, so that *the rate of change* of the current will show a rapid increase to a maximum. It will remain at this maximum for a certain range of voltage, and then fall as that value of anode potential is approached which is sufficient to draw *all* the electrons temporarily released by the cathode across to the anode, when any further increase of potential will have no effect in increasing the current. This condition will give the maximum, or *saturation current* for the valve, at that particular temperature of the filament.

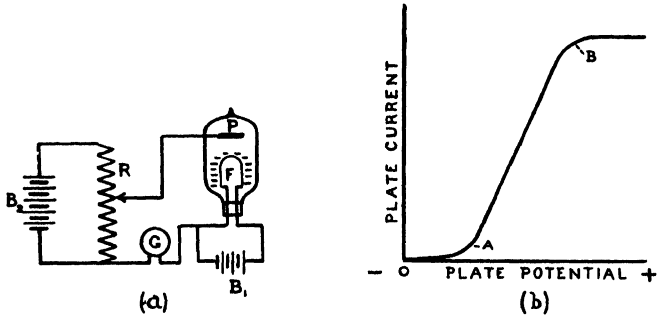


FIG. 85.—Test Circuit and Plate Characteristic of Two-Electrode Valve.

We can show this relation very well by substituting a battery, B_2 (Fig. 85 (*a*)), with potentiometer resistance, R, for the oscillatory circuit JC of Fig. 84, and a current-measuring instrument, G, for the telephone. Then, as the potentiometer slider is moved towards the positive end of the battery—thereby increasing the positive charge applied to the plate—the plate current will increase and finally arrive at a steady value, as shown by the curve (Fig. 85 (*b*)), known as the *plate characteristic.*

If necessary, we can obtain a series of characteristics OA, OB, OC, OD, etc. (Fig. 86), by taking readings over the same range of potential for different values of the series resistance, *r*, in the filament circuit. If *r* is decreased, the filament temperature is increased, and therefore also the number of electrons available as current carriers, and in consequence the saturation current.

Now the rectification effect is measured by the difference of the two currents in the plate circuit obtained when a given potential is first added to the plate and is then subtracted from it.

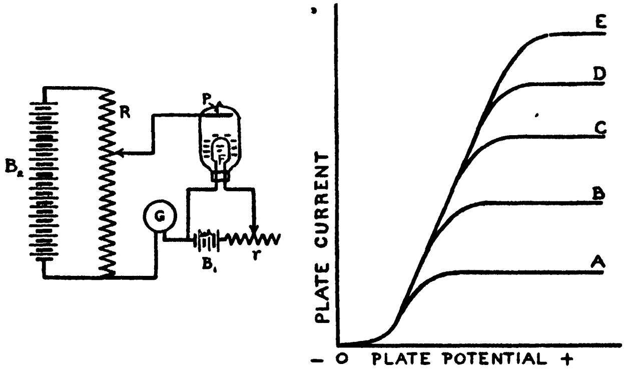


Fig. 86.—Circuit Connections for taking Two-Electrode Valve Characteristics at different Values of Filament Current.

If this potential is very low, it involves only a very small part of the characteristic shown in Fig. 85 (*b*), and the rectification current will be proportional to the change of slope only over that part.

But it is obvious from the shape of the curve that the change of slope, for equal increments of potential, is not constant, and the greatest rectification effect is therefore to be expected where the *rate of change* is greatest—that is, either at the lower bend A or the higher one B.

The actual signal current, as obtained with the circuit of Fig. 84, is very small, and the change of potential it represents in the plate circuit is also very small; so that, to obtain the greatest rectification effect, it is advisable to use an additional source of potential to bring the working point of the valve to the bends A or B on the characteristic. This is provided for by the potentiometer circuit R, shown in Fig. 87, and the potential due to the signal current therefore causes the telephone current to vary above and below a steady value obtained from the battery B.

But if the valve should be working on its characteristic between the points A and B (Fig. 85 (*b*)), it will show no rectification effect, for there is no change of slope, and an alternating potential applied to the plate will therefore increase the plate current by the same amount as it is decreased, so that the mean current through the telephone will remain the same. Thus adjusted, the valve behaves as if it has a constant resistance, which is a quality which does not lend itself to any useful application in the two-electrode valve.

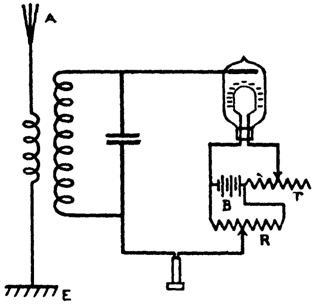


Fig. 87.—The Plate Potentiometer.

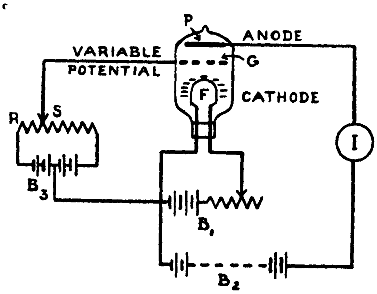


Fig. 88.—The Three-Electrode Valve Circuits.

The Three-Electrode Valve and the Amplification Effect.—A development in valve construction will now be discussed which does allow the straight part of the working characteristic to be usefully employed, and also causes it to have a very much greater steepness.

This development is a third electrode G (Fig. 88), which was introduced into the valve by Lee De Forrest in the year 1913, with the object of using the valve action between two of the electrodes to control a relay current passing from one of them to a third.

In this arrangement, two circuits are established through the valve, B_2FPIB_2 and B_3FGSB_3, in which the filament F is made a common electrode.

The filament is heated in the usual manner, so as to provide a semi-free charge of electrons.

It is made the cathode in the relay, or "plate" circuit, so that under the influence of an E.M.F. these electrons tend to be drawn on to a metal plate acting as the anode.

The potential applied to the anode is maintained constant, so that for any given temperature of the filament, the electron current to the anode which results should also remain constant if only the plate circuit had to be considered, and it could be given any value, depending on the E.M.F. applied, up to that of the saturation current for the valve.

But variability is impressed on this plate current by means of a control electrode, G, commonly called the "grid," which consists of a wire mesh, grid, or spiral, placed near to the filament—sometimes surrounding it—and in the direct line of the electron discharge. The grid can be made either positive or negative relative to the filament, by means of an auxiliary circuit having a return to the valve through the filament.

In the connection diagram (Fig. 88) the valve is brought to the working point of its characteristic by moving the slider, S, on the potentiometer, R, until the correct potential is applied to the grid from the battery source, B_3.

Suppose we impress a negative charge on the grid.

Then the electrons which are streaming through it to the plate will experience a repelling force, tending to drive them back to the filament.

The plate current, I, will therefore be reduced. If the negative potential on the grid is sufficiently increased, the electrons will be unable to pass the grid; they will remain as a *space charge* between it and the filament, and the plate current will cease.

A further increase of negative potential will tend to reduce this space charge by driving the electrons back into the filament. As the grid is negative, and the plate is positive, and their external circuits communicate, it might be thought that a current would pass between them; but any such current would have a negligible value, as the grid temperature is too low to cause thermal expulsion of the electrons, and the number freed by other causes is so few that the leakage current due to them would be hardly felt.

But suppose we impress a positive charge on the grid. This will encourage the electron discharge, and the grid being nearer to the filament than is the plate, a larger increase in electron current will result than if the same charge were added to that already on the plate, the grid not being present.

The valve electron current will divide, so that only a small part of it will feed the grid circuit, while the greater part—owing to the plate voltage being maintained much higher than that of the grid—will traverse the grid and enter the plate circuit.

As the positive potential of the grid is increased, more and more current will flow to the plate, until the saturation value is reached. This value depends on the total number of electrons released by the filament, minus that fraction which is diverted into the grid circuit as current, so that in the case of a "hard" valve, or one having negligible gas content, if the grid circuit and plate circuit were to have equal resistance, the sum of the two currents at saturation would be approximately the same as the saturation current through the plate circuit when the grid is not in use.

It can now be understood how a small change of potential on the grid is able to cause a large change of current in the plate circuit. The increased sensitiveness of the three-electrode valve due to this amplification effect, as compared against the same valve used with two electrodes only—the grid being disconnected,—is indicated in Fig 89, where OP is the plate characteristic, and QG the *grid-plate characteristic.*

For the same change of current $(I_2 - I_1)$, a change of potential of $V_1 = 4$ volts, is required in the first case, and $V_2 = 50$ volts in the second.

The values of grid and plate potentials are given relative to that of the end of the filament connected to the negative pole of the battery, which is taken as zero.

Fig. 90 shows an interesting family of such curves. Curve OP is the plate characteristic given by a certain valve on a constant filament current, the third electrode not being in use.

When this valve was worked with a constant potential of 45 volts on the plate, that is at point A on OP, and the grid potential was varied above and below zero, it gave the grid-plate characteristic 9A. At the same time the current through the grid circuit gave the curve OA.

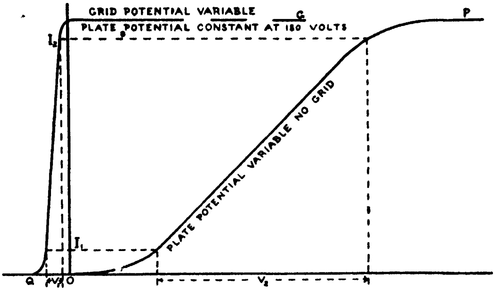


FIG. 89.—Three-Electrode Valve compared against a Two-Electrode Valve for Sensitivity.

Another pair of grid characteristics, 17B, and OB, were obtained using 90 volts on the plate, that is when working at the point B on curve OP, and still further tests with 135 volts, and 180 volts on the plate, gave the curves 20C, OC, and 30D, OD, respectively.

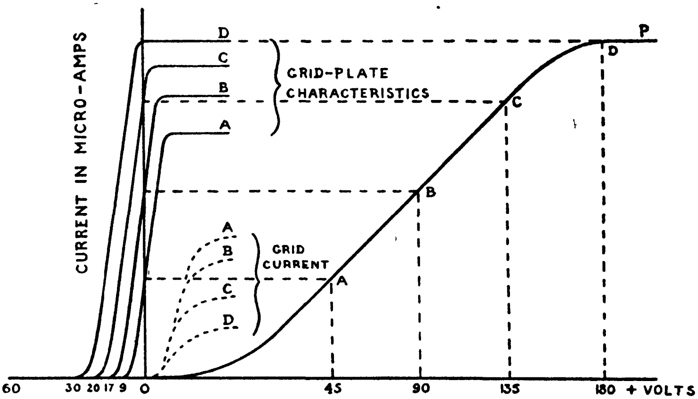


FIG. 90.—Grid-Plate Characteristics, at different Plate Voltages.

An examination of Fig. 90 shows that the grid voltage required to produce a rectification effect—when the valve works on a bend of the curve,—or an amplification effect—when the valve works on a straight part of the curve,—is very different for the various plate voltages applied; although, as the curves are practically parallel, the *degree* of amplification or rectification within certain limits remains very much the same.

Where the principal difference arises is in the relation of the grid current to the plate current.

It will be seen that as long as the grid potential is negative there is no grid current, so that if, by means of the potentiometer slider, we adjust the potential on the grid to a value on the straight part of the curve, and then superpose on it a sine wave alternating potential such as would be caused by a signal current, then, if these alternations do not cause the grid to become at any time positive, true amplification will result, as the amount the plate current is increased above the normal will be equal to the amount it is decreased below the normal.

When, however, the grid is made positive, a grid current flows which has a comparatively high value for low plate voltages, and a low value for high plate voltages.

The grid current, as we know, consists of a stream of negatively charged particles drawn off from the filament, so that its effect is to partly neutralise the positive charge on the grid. The result, therefore, of superposing a sine wave signal current on the grid circuit such as will cause the grid to alternate from negative to positive, will be to cause an unequal variation in grid voltage above and below the normal, so that a rectification effect will be introduced.

If the grid always remains positive during the alternations of signal current, then whether amplification takes place or rectification will depend on the relative slopes of the two current curves; but in any case the results will not be so good as those obtained when the grid adjustment is such that it always remains negative.

Amplification of small signal currents can best be obtained, therefore, with medium plate voltages and a negatively charged grid, amplification of heavy current by using high plate voltages and a more negatively charged grid.

But where rectification alone is required, quite low plate voltages may be used with low grid potentials, as the valve will then be working on the lower bend of the characteristic.

The effect of altering the valve filament current is shown in the series of curves of Fig. 91. These curves resemble those obtained when the filament current of a two-electrode valve is varied, as shown in Fig. 86, in that the potential required to produce a saturation current moves to the right as the filament current increases; but with the three-electrode valve this also means that the grid potential required to produce amplification becomes increasingly positive, and that there is current in the grid circuit.

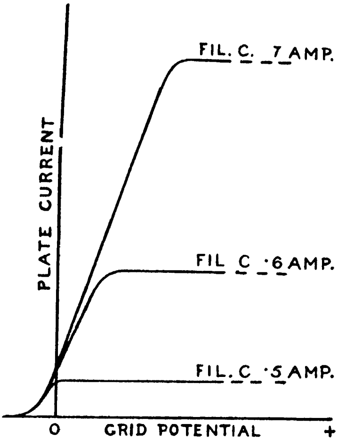


FIG. 91.—The Effect of altering the Filament Current on the Grid-Plate Characteristic.

The advantage of keeping the grid always negative relative to the filament is the reason why the filament is sometimes connected to the positive end of the heating battery, as shown in Fig. 92.

This allows a smaller negative charge to be used on the grid than if the filament were connected to the negative end of its battery, and therefore fewer cells are necessary in the grid potentiometer circuit.

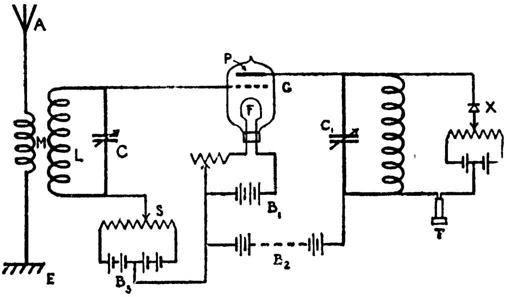


FIG. 92.—The Filament connected to the Positive End of the Heating Battery.

Then the operations which take place in a simple amplifying receiver circuit, such as is shown in this same figure, are as follows:

The signal current generated in the aerial circuit AME transfers its energy by means of the coupling coil, M, to the circuit LC, which is tuned to the incoming frequency by the variable condenser C. This causes a small high-frequency potential to be impressed on the grid of the valve, which results in a variation of the plate current at the same frequency.

The plate circuit is tuned to the frequency of its supply by the variable condenser, C_1, and its resonance potential is then impressed on the crystal, X, in the detector circuit.

The crystal causes a rectified current to flow through the telephone, T, and, as this current has been given a *group* frequency, as distinct from its wave-length frequency, which is well within the audible range, the telephone gives out an audible note.

As the amplification will be the same anywhere on the straight negative part of the grid-plate characteristic, the position of the slider, S, nearest to the centre of the potentiometer, which gives strongest signals on the telephone, T, in the crystal detector circuit XT, will be the best to use.

High-Frequency Amplification takes place when the signal current—or its derivative—is amplified *before being rectified*; when, in fact, the current has such a character that it is unsuitable to apply to a telephone. The example given in Fig. 92 is a typical case.

Low-Frequency Amplification is the process applied to the signal current *after its form has been altered by rectification* so that it can affect a telephone. Such an arrangement is shown in Fig. 93, the rectified current applying a variable potential to the valve grid by the aid of the step-up iron core transformer T. Both forms of amplification have their special uses and their limitations.

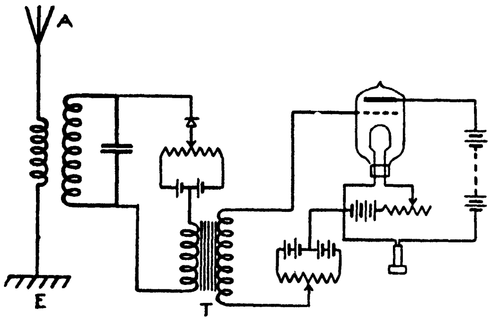


FIG. 93.—Low-Frequency Amplification.

H.F. amplification allows very selective circuits to be used on a receiver, for no matter how weak the signal current is made by such circuits, it can be amplified up again before rectification.

But very strong signals may not always require H.F. amplification. They can be weakened by loose coupling selective devices to the minimum strength required for efficient working of the rectifier, and the rectified current can be strengthened by L.F. amplification—also known as "note magnification"—before it reaches the telephone.

The same arrangement applied to weak signals, however, would allow less selective tuning to be used, and therefore more interference would be amplified into the telephone circuit in addition to the signal current required.

The Efficiency of Rectification, whether by valve or crystal, depends very considerably on the magnitude of the current to be rectified.

Let us take a typical valve characteristic (Fig. 94); then greatest rectification will be obtained if we apply an E.M.F., OB, to the grid, so that the valve will function at the point A, where the rate of change of slope is greatest.

Suppose a small E.M.F., *v*, due to a current I, in the circuit LC (Fig. 96), to which it is directly proportional, is added to the grid potential OB. This will cause the plate current to rise to the value FE. Subtracting the same small E.M.F., *v*, from the grid potential OB, will cause the plate current to fall to the value CD.

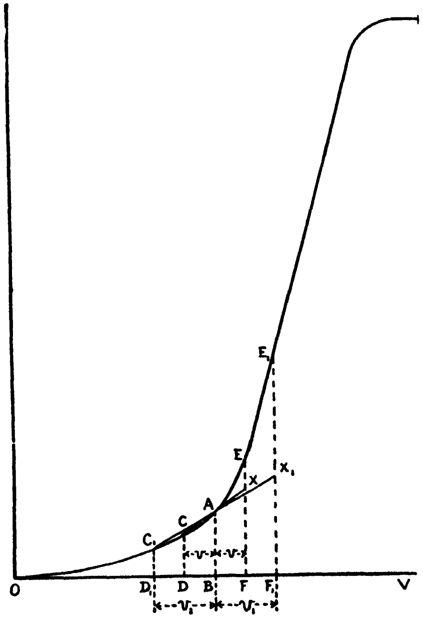


FIG. 94.—Comparison of Rectification obtainable with Small and Large E.M.F.

Rectification results when the current increase above the normal is different from the current decrease, and, for simple alternating E.M.F.'s, it can be shown that its value is given in the diagram by the current EX, obtained by extending the straight line joining CA until it cuts EF at X.

But suppose now that a larger alternating E.M.F. of value v_1, due to a corresponding current I_1, is applied to the grid potential OB, such that the maximum and minimum currents which result are E_1F_1 and C_1D_1 respectively. Then the line joining C_1 to A cuts E_1F_1 at the point X_1, and E_1X_1 is therefore the rectification current, which is seen to be much greater in proportion to EX than is v_1 to v, or I_1 to I.

This is one reason why, with weak signal currents, it is very desirable to amplify them first and rectify them afterwards, instead of carrying out these operations in the reverse order.

If there is *any signal at all* it can be brought up to normal working strength for efficient rectification by using suitable amplifying devices, but a weak signal may be mutilated or lost altogether by attempting first to rectify it.

A crystal detector circuit, for instance, which includes telephones, requires a certain minimum amount of energy to produce audible signals.

If the aerial supplies less than this minimum amount, it can be utilised if it is passed through an amplifier before it reaches the crystal, but it will be wasted if it is required to work the crystal circuit before affecting the amplifier.

The Plate Current Retro-Active Effect.—A single valve, with the best adjustment possible of a simple amplifying circuit, may not be able to bring the H.F. current up to the requisite strength for efficient rectification.

If, however, we cause the small amplified current in the plate circuit to react back on the grid circuit, and in such a manner as to assist the grid current and therefore to build up the grid voltage, then a still greater plate current will be produced.

This is the purpose of the *reaction coil*, R, shown in the two diagrams of Fig. 95, introduced by C. S. Franklin, which, by means of its inductive coupling, transfers a small part of the energy released in the plate circuit back to the grid circuit, and thereby boosts up the grid voltage, and consequently the plate current, to a much higher value. In diagram (*a*) retro-action is being introduced to improve the rectifying action of the valve, and in diagram (*b*) to improve amplification.

The energy required for this process is taken from the plate battery; all that the signal E.M.F. does is to release it, and the amount used depends on the degree of coupling of the reaction coil to the grid circuit, which is necessarily made adjustable.

So much energy may be given to the grid circuit in this way as to compensate for all its losses, so that its oscillations are permanently maintained, and the valve and its circuits as a whole act as a continuous oscillator, the transfer of energy taking place from the plate circuit to the grid circuit, and then back from the grid to the plate circuit again. This state is not what is required for the reception of spark signals, as it would continue after the signal current in the aerial had ceased. The coupling of the reaction coil should therefore be adjusted below the value which will bring this condition about.

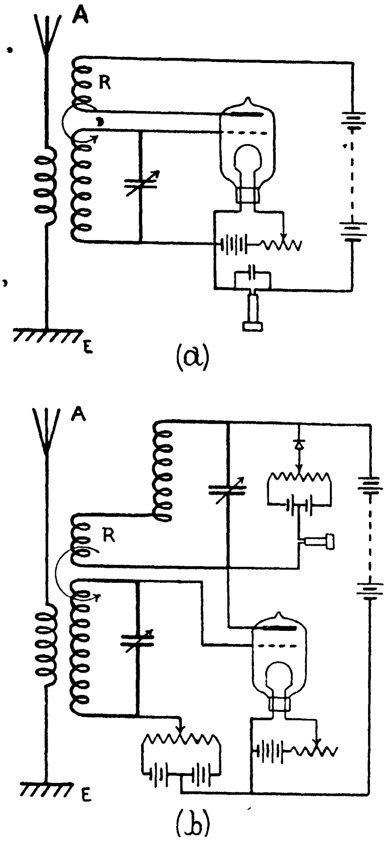


Fig. 95.—The Use of a Reaction Coil.

Instead of using a magnetic coupling, a reaction effect can be obtained by connecting the two circuits through a suitable condenser and resistance, or even by a simple resistance alone; although the *capacity coupling*, which always exists in some measure between the valve circuits, while it can often be usefully employed, is very often a disadvantage to a receiver, as it renders it less selective, and may, under certain conditions, cause the valve to work in an unstable manner.

Simple and Cumulative Rectification.—In simple rectification, the grid, G (Fig. 96), is given a certain small negative potential with reference to the filament by means of the potentiometer, P, in order to make the valve function at the bend of its characteristic.

If (*a*) represents two wave-trains induced in the tuned oscillatory circuit, LC, by the signal current in the aerial, AE, then the variation of potential on the grid which results is shown by (*b*). The change in the plate current which takes the path through the condenser shunting the telephone is shown at (*c*), and the effective current through the telephone winding by curve (*d*)—the large inductance of the instrument having the effect of heavily damping the oscillations down to a mean current value.

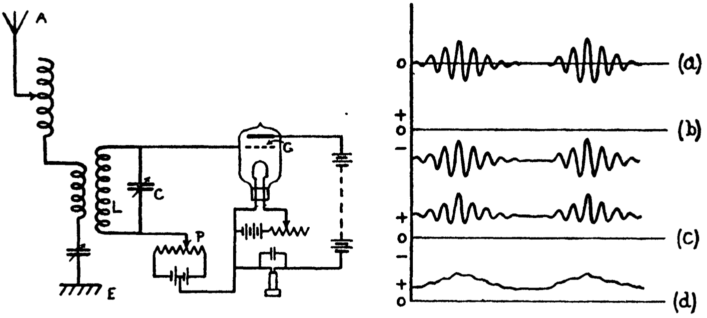


FIG. 96.—Simple Rectification.

By inserting a small condenser, C_1 (Fig. 97), in the grid circuit, we can obtain a *cumulative rectification effect*, and we can then afford to work without a grid potentiometer.

We may assume that the grid, to begin with, is at the same potential as the filament (Fig. 97 (*b*)).

When the oscillating current in LC makes the grid more positive than the filament, a flow of electrons from the filament results, which neutralises the grid charge; but when the grid is made more negative, there is no flow from the filament, and the charge—which is prevented from returning into the grid circuit by the condenser C_1—is retained by the grid.

Every succeeding complete oscillation in LC tends to add something to the negative potential of the grid, so that at the end of the wave-train it has reached quite an appreciable value (see Fig. 97 (*b*)), and the plate current, as shown by Fig. 97 (*c*), falls by a proportionally large amount. The telephone current curve is indicated at (*d*), and the amplitude of the telephone diaphragm is proportional to this current. The valve, or its circuits, must now provide some means of discharging the grid in order that it may return to its original state for receiving the next wave-train.

Soft valves, or those which contain gas, bring this condition about by means of the positive gas atoms, which bombard the grid and cause its potential to slowly fall; but with hard valves it is necessary to provide a resistance leak, *r*, across the condenser of several thousand ohms, to produce the same effect.

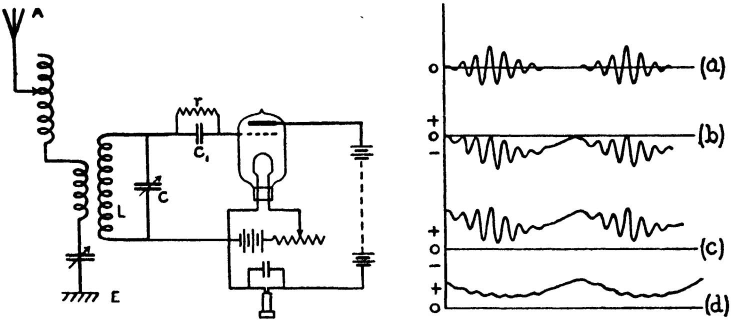


FIG. 97.—Cumulative Rectification.

The Production of Continuous Waves by means of an Oscillating Valve.—Given a retro-active valve circuit as described on page 121, it is a simple matter to so arrange its adjustment as to turn it into a valve generator of continuous oscillations.

On making contact with the operating key, K (Fig. 98), which is placed in the grid circuit, a certain potential—which is determined by the position of the slider on the potentiometer, P,—is applied between the grid and the filament.

This causes a variation in the plate current flowing through the inductance coil LR, which is sufficient to start a small oscillation in the circuit LRC.

The resulting current reacts by the induction of the magnetic field due to the coil R on the grid circuit, causing a variation in grid voltage, which can be given considerable amplitude if the grid circuit is tuned to the frequency of the plate current.

The coupling of R is adjusted so that just sufficient energy is fed into the grid circuit to keep the valve oscillating, and this action continues as long as the key K is depressed.

To apply this valve oscillator to an aerial in order to transmit signals, it is simply necessary to couple the aerial to the plate circuit—that is, where the energy is greatest—by means of an inductance coil, as shown at L_A (Fig. 99), and arrange that the aerial and the plate circuit are in tune.

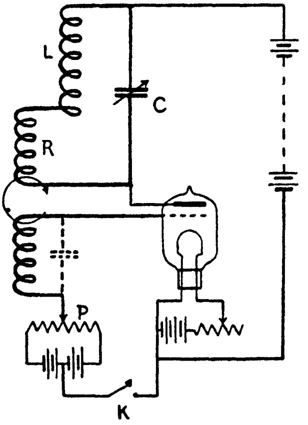


FIG. 98.—A Three-Electrode Valve Circuit for the Generation of Continuous Waves.

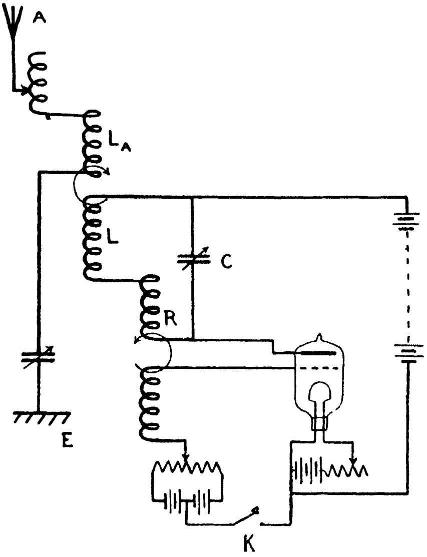


FIG. 99.—A Valve Oscillator coupled to an Aerial.

If the coupling is made too strong, two widely different oscillation frequencies will be produced, and the corresponding waves which are radiated will divide the transmitted energy between them. Clearly, a weak coupling will be much better, as all the energy will then be radiated by two waves differing so little in length as to be equivalent to a single wave-length.

Fig. 100 shows a simplified form of continuous wave transmitter which can be used when the self-capacity of the valve is very small compared with the capacity of the aerial. The reaction coupling is adjustable, but the aerial coupling is made direct to the plate circuit.

In Fig. 101 the plate battery has been replaced by a high-tension machine D, which is shunted by a large condenser C_D of about 1 or 2 mfds. capacity, in order to wipe out any inequalities in the voltage applied to the valve, which cause noises in the telephone at the receiving station. An oscillogram of the E.M.F. of a 150-watt 2000-volt D.C. generator is shown in Fig. 102 (*a*). When a condenser of 1 mfd. capacity was connected across its terminals, the machine delivered an almost unvarying voltage supply to the plate circuit of a valve, as shown by the oscillogram, Fig. 102 (*b*), although the current through the machine itself—Fig. 102 (*c*)—was very rippled. It will also be noted in Fig. 101 that the battery voltage applied to the grid is fixed. Reference to the curves of Fig. 90 and Fig. 91 will show how this reduction in adjustment can be made possible.

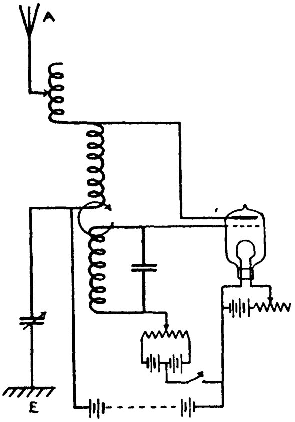


FIG. 100.—A Simplified Form of Valve Oscillator Circuit.

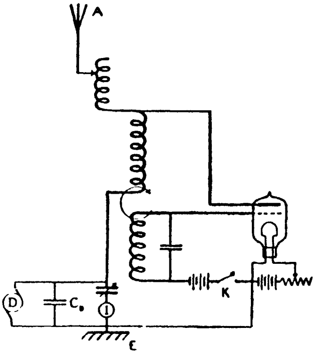


FIG. 101.—A High-Tension Generator used in place of a Plate Circuit Battery.

The valve is acting as an amplifier, and therefore should be working on the straight part of its grid-plate characteristic.

Then if we fix the voltage applied to the grid, we can adjust the valve to the required working position by either altering the filament current—which shifts the position of the top bend of the characteristic while it hardly affects the lower bend,—or we can alter the plate voltage—which shifts the characteristic bodily, with very little change of slope, to the left for an increase, and to the right for a decrease.

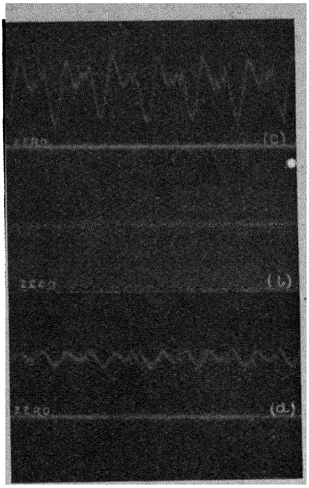


FIG. 102.—Oscillograms showing the Effect of a Condenser on a Fluctuating Direct Current Supply.

For preference the filament current should be adjustable, and both grid and plate potential fixed.

The Reception of Continuous Waves.—In order to detect continuous wave signals it is necessary either to break the signal current up into groups of oscillations, or else to create a "beat" in it by causing its amplitude to vary periodically, the group or beat frequency coming within the limits of audition, that is between 10,000 and 20 per second. If this is not done, a click will be heard in the telephone at the beginning of each signal, and a click at the end, but nothing more.

The signal current can be chopped up by means of a mechanical interrupter, or "tikker," in the aerial, which breaks circuit the required number of times per second, or by using an imperfect contact such as that given by a fine—but clean—wire, bearing in a V-groove on a running metal pulley.

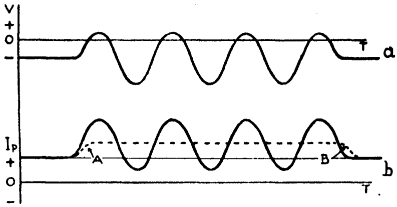


FIG. 103.—The Rectification of Continuous Oscillations.

But the most practical and efficient method is to make use of an independently-generated, continuous-wave current, to create beats by interference in the receiver circuits with the incoming signal current.

Let Fig. 103 (a) represent a series of potential oscillations of unvarying amplitude due to the signal current, which have been started in the grid circuit, and the full line curve of Fig. 103 (*b*) the resulting plate current; if the high inductance of a telephone is included in the plate circuit, the ripples in (*b*) will be damped out, and the mean current shown by the dotted line will result. A click will be heard in the telephone at the beginning of the signal at point A on the curve, where the mean current rises, and another click at the point B, where the signal ceases and the mean current falls.

Now suppose an additional current, (*b*) (Fig. 104), is induced in the grid circuit, of slightly greater frequency than the signal current (*a*) (Fig. 104).

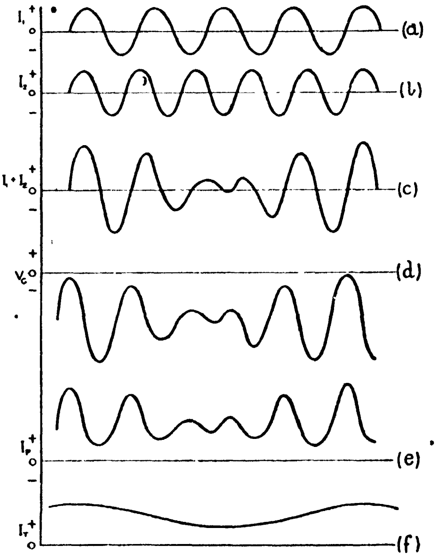


FIG. 104.—Two Sets of Continuous Oscillations of different Frequency employed to produce a Beat Frequency.

Then the resultant current curve Fig. 104 (*c*), obtained by superposing (*a*) on (*b*), is seen to contain "beats," that is, a harmonic sequence of maximum and minimum amplitudes.

The potential applied to the grid (Fig. 104 (*d*)) varies in a like manner, so that with the valve adjusted to act as a rectifier, a plate current such as is shown in Fig. 104 (*e*) will be obtained, and the current through a telephone arranged in shunt to this circuit will be undulatory in character (see Fig. 103 (*f*)), the number of undulations corresponding to the beat frequency, which will be determined by *the difference between the signal current frequency and that of the impressed current.*

In Fig. 105 the signal current oscillations set up in the aerial circuit ALCE mix with oscillations of very nearly equal frequency produced by the generator, G, which are induced into the same circuit by means of the coupling coil, M.

The beat current which results therefrom in L causes a variation in the grid potential applied by the potentiometer, P, and the telephone in the plate circuit responds to the beat current.

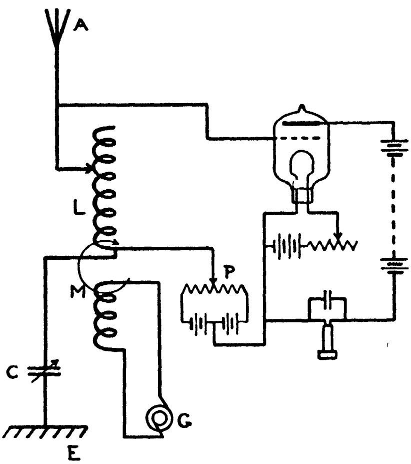


FIG. 105.—An Arrangement of Circuits employing a separate Generator to produce a Beat Note.

The independent generator, G, can be replaced by a modification in the valve circuit, as shown in Fig. 106.

The rectified current in the plate circuit, PL_1MBF, impulses the circuit L_1MC_1, which is tuned by the condenser C_1 to almost the same frequency as the received signals. The oscillations started in L_1MC_1 are then made to react back on the aerial circuit by means of the coupling coil, M, so as to produce a beat current, which, in its turn, creates a beat potential on the grid, and consequently a variation in amplitude of the telephone current such as is required for note signals.

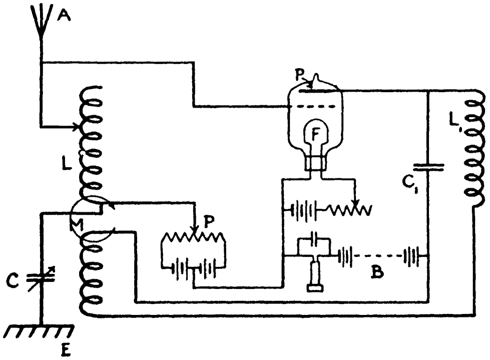


FIG. 106.—A Valve Circuit arranged as a Self-Beat Generator and Detector.

The Oscillating-Valve Telephone Transmitter. — In this case the circuits of the three-electrode valve are arranged as for a continuous wave oscillator, with coupling to an aerial to form a radio transmitter.

The resistance of a microphone, which can be varied by speaking into its mouthpiece, is then used to control the amplitude of the aerial current, either by inserting the microphone direct in the aerial circuit, or by suitably coupling it to some other part of the complete transmitter. Fig. 107 shows a simple direct arrangement, capable of giving good results.

The retro-active effect of the plate oscillatory circuit L_PC_P, on the grid circuit, is adjusted by means of the coupling to the point at which continuous oscillation takes place, the frequency of oscillation being set by means of the adjustable condenser C_P to that of the aerial.

The inductive coupling between L_A and L_P, whereby the aerial circuit is caused to oscillate, is adjusted to that degree at which the maximum glow takes place in the tuning lamp T, at one position only of the variable condenser C_P. If two such positions are found, the coupling should be weakened.

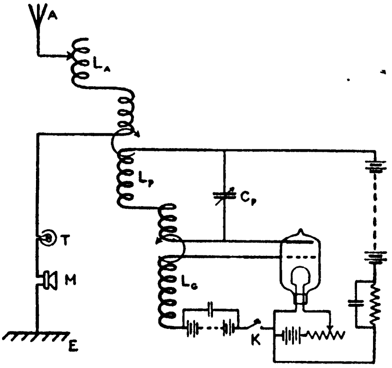


FIG. 107.—A Valve Telephone Transmitter, with Microphone in the Aerial Circuit.

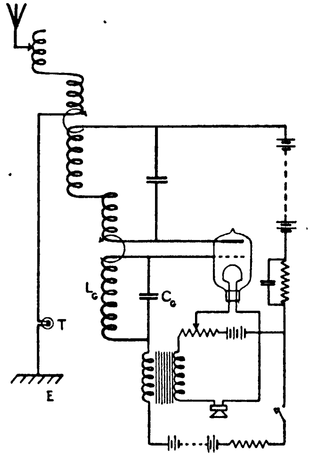


FIG. 108.—A Valve Telephone Transmitter with Microphone arranged to affect the Grid Circuit.

With this adjustment made, the valve and its circuits can be used as a telegraph transmitter by operating the key K in the grid circuit. For telephony, K is closed, and the operator speaks into the microphone M, which is inserted in the aerial lead to earth.

An alternative circuit is illustrated in Fig. 108.

The microphone is made to affect the grid circuit through the intermediary of a step-up transformer, the current for the microphone being obtained from the filament battery.

As the transformer secondary winding is likely to increase the natural period of the complete grid circuit to a value greater than that of the aerial, it is advisable to use a tuning condenser C_G, across the inductive coil L_G, in order that the resonance effect of at least part of the circuit with the aerial wave-length may be made use of.

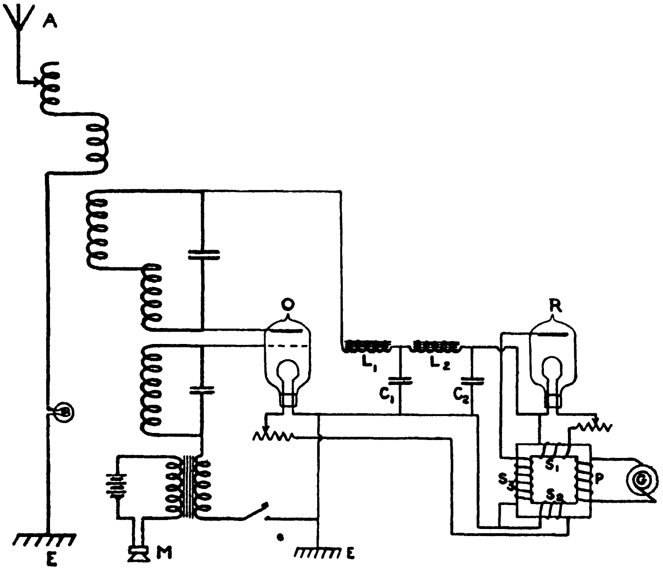


FIG. 109.—An A.C. Generator employed with a Valve Telephone Transmitter.

The Use of A.C. Generators for Valve Circuits.—The employment of high-tension batteries for the plate voltage supply, although very convenient, has certain drawbacks. The batteries are expensive, they require to be renewed frequently, they are affected by climate, and it may not always be possible to get renewals.

Under certain conditions an alternating current supply may be used with advantage. Its application to a wireless telephone circuit is illustrated in Fig. 109.

Current is taken from the alternator G, to the primary P, of a transformer.

A secondary winding, S_1, provides a low-tension heating current for the filament of a two-electrode rectifier, R.

A high-tension secondary winding, S_3, which has one end earthed, applies a potential of 6000-9000 volts to the plate of the valve R, and on completing the circuit a rectified broken current passes between the plate and the filament.

The plate-filament circuit of the oscillating valve O, is directly in series with the plate and filament of the rectifier, but the current in flowing from one to the other has to pass through a series of inductance coil and condenser combinations, L_2, C_2, and L_1, C_1, etc., which have the effect of wiping out the fluctuations in the supply.

The heating current for the filament of the oscillating valve is also supplied by the same transformer from a secondary winding, S_2, one end of which is earthed.

The only battery used in the complete transmitter is therefore that in the microphone circuit.

If the adjustments are suitable, noise from the A.C. supply is practically eliminated.

Types of Three-Electrode Valve.—Several forms of Marconi-Round three-electrode valve are illustrated in Fig. 110.

The transmitting valves are marked "T," and the receiving valves are marked "R." Their working conditions are tabulated below:—

No.	Type.	Plate Volts.	Filament Current.
T_1	M.T. (1)	6000-9000 volts rectified A.C.	5 amps.
T_2	T.N.	2000 volts D.C.	4-4·5 amps.
T_3	L.T.	1500 „ „	1-1·2 „
T_4	S.	800 „ „	1 „
R_1	N.	40-80 volts D.C.	2·5 amps.
R_2	C.A.	200 „ „	2·5 „
R_3	Q.	150-200 „ „	0·35-0·4 „
R_4	V 24.	24-50 „ „	0·7 „

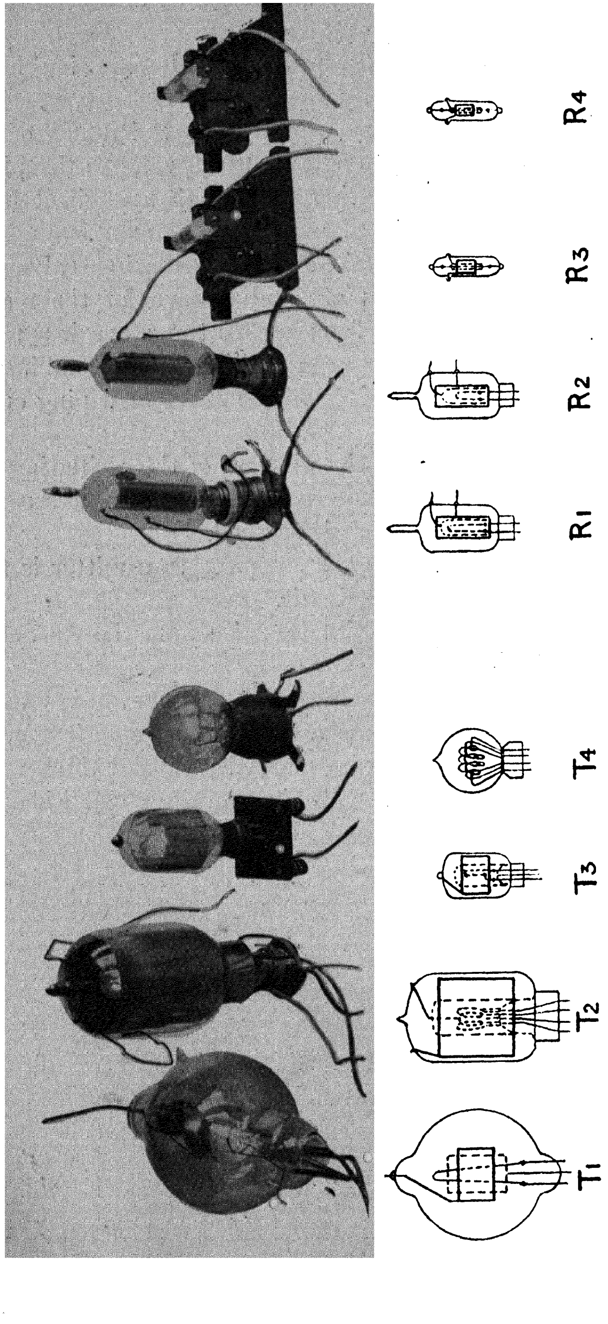


FIG. 110.—Types of Three-Electrode Valve.

The filaments are looped in T_1, T_2, R_1 and R_2, and straight in T_3, T_4, R_3 and R_4; T_2 having three filaments which are used separately—when one burns out, another is used.

The grids—with the exception of that of T_4, which is a wire spiral—are all cylinders of narrow-mesh wire gauze.

The plates—with the exception of that of T_4, which is a wire spiral—are all cylinders of sheet metal.

R_2 is not now in use.

Oscillation Valve Instruments.—The various effects of rectification, amplification, and retro-action, which have been separately discussed, are often combined in the modern valve receiver, or transmitter, as will be seen in the descriptions which follow of some of the types now used in practice.

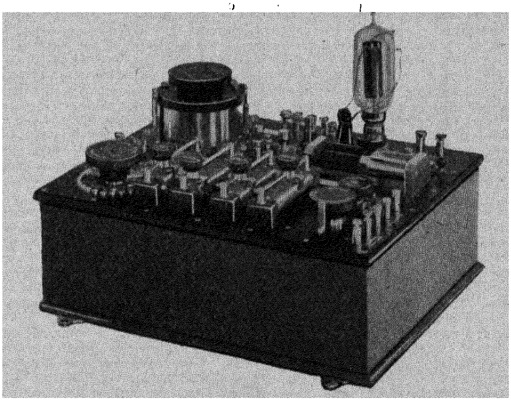


FIG. 111.—Marconi Receiver, Type No. 27.
General View.

Marconi Receiver, Type No. 27.—This instrument (Fig. 111) has a wave-length range of 600 metres to 5000 metres; it can receive either spark signals or continuous waves, it is provided with both crystal detector and valve; balanced crystals can also be employed if atmospherics are troublesome.

A plan of the top of the instrument is shown in Fig. 112 (*a*). The scheme of connections for receiving spark signals, which comes into play when the change-over switch S_4 is in the position given in the diagram, is that of Fig. 112 (*b*).

The aerial circuit is provided with an adjustable inductance L_A, and variable condenser C_A, for the purpose of tuning, and a reaction coil L_R with a tapping for use with short waves.

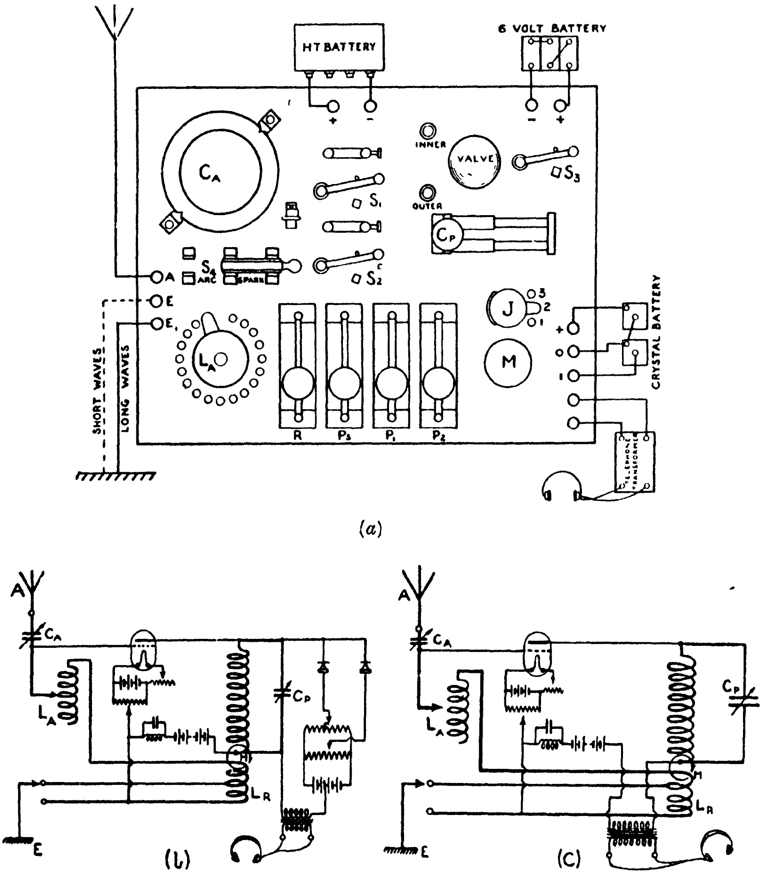


FIG. 112.—Marconi Receiver, Type No. 27.

(*a*) Plan of Top of Instrument. (*b*) Scheme of Connections for receiving Spark Signals. (*c*) Scheme of Connections for receiving Continuous Waves.

The oscillatory part of the plate circuit includes an adjustable billi condenser C_P, and an inductive winding having three tappings to which connection is made by the switch J.

The valve is used as an amplifier. The signal current is boosted up by the retro-active effect of the coupling at M, and either one or both of the crystals are used as detectors. A low-resistance telephone is coupled to the detector circuit through a transformer. If the valve filament current is switched off, the instrument becomes a plain crystal receiver, the coil L_R with its variable coupling acting as the jigger primary, and L_P as the jigger secondary.

When the switch S_4 is changed over to the position marked ARC, the crystal detector circuit is permanently opened, and the telephone transformer is removed from it to the plate circuit, as shown in Fig. 112 (*c*).

The valve now acts as a rectifier; by adjusting the condenser C_P the plate oscillatory circuit is slightly mistuned to the aerial wave, so that by retro-action back on the grid circuit through the coil M it can produce beats, which, in their turn, can be rectified and thus give audible signals.

A 6-volt 40-ampere-hour accumulator battery is provided for the valve filament, a 200-volt dry-cell battery for the plate circuit, and a 2·8-volt dry battery for the crystals.

The valve itself is of the "N" type; it takes 2·5 amperes through the lime-coated platinum filament and is provided with means for lowering the vacuum should it become too "hard." A safety resistance of 2000 ohms is always used in the plate circuit.

Marconi Field Station Receiver, Type No. 38 (a)—This is an example of a receiver which makes use of one valve as a detector, and then employs two other valves to progressively amplify the rectified signals. Fig. 113 gives a general view of the instrument, and Fig. 114 a simplified diagram of its connections.

The aerial circuit includes an adjustable inductance and condenser, and a coupling coil which acts as a jigger primary, the jigger secondary being the coil L_G, tuned to resonance by means of the adjustable condenser C_G, which is connected to the grid and filament of the first valve which acts as a rectifier.

The plate circuit of this valve includes the primary of an iron core transformer, the secondary winding of which

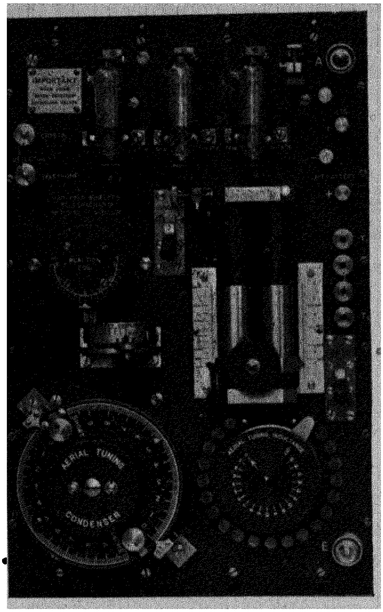


FIG. 113.—Marconi Field Station Receiver, Type No. 38 (*a*). General View.

transfers the rectified signals to the grid of the second valve. The transformer primary and the high-tension battery are short circuited for high-frequency currents by means of condensers, so that it is possible to employ a reaction coil L_R to boost up the signal current in the grid circuit, in order to amplify the rectification.

The rectified pulses through the coil L_R have the character shown in Fig. 96 (*c*), whereas those through the primary of the transformer resemble the undulations of Fig. 96 (*d*).

The second valve performs the function of a low-frequency amplifier, and a telephone transformer inserted in its plate circuit allows signals to be obtained on a low-resistance telephone. This same transformer, however, has a

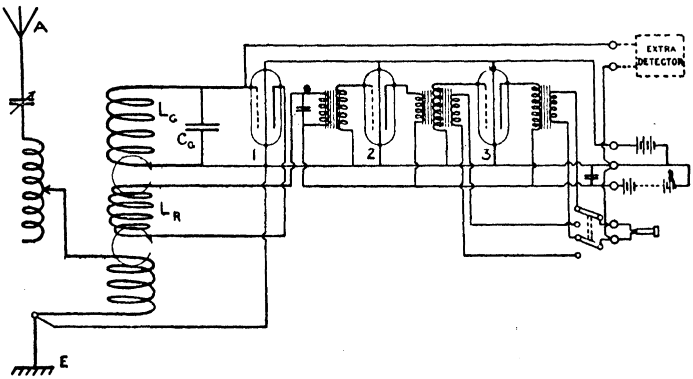


FIG. 114.—Marconi Field Station Receiver, Type No. 38 (*a*). Scheme of Connections.

tertiary winding by means of which these signals can be handed on in the form of potential variations to the grid and filament of the third valve, to receive there further amplification, and a switch is provided in order to transfer the telephone from the second valve to the secondary of a transformer included in the plate circuit of this third valve.

The three valves have different functions, and therefore should work on relatively different parts of their characteristics.

No. 1, the rectifier, requires an adjustment which should make it work on either the upper or lower bend.

No. 2, which amplifies on the application of medium rectified potentials, requires to work on the straight part of the curve, and so that it does not reach either bend within the range of potentials employed; while

No. 3 amplifies on higher rectified potentials, and therefore requires to work on a still longer straight part of the curve.

These adjustments are achieved without applying any battery potentials to the grids, which is an advantage in a Field Station instrument as the provision of additional cells for this purpose is thus avoided.

The method used is to run the filaments at different current strengths. They are connected in parallel to the same battery but through resistances of different values.

As a result the filament of No. 1 is dull red, and as shown in Fig. 115 at zero potential on the grid the valve will be working on the top bend of its characteristic.

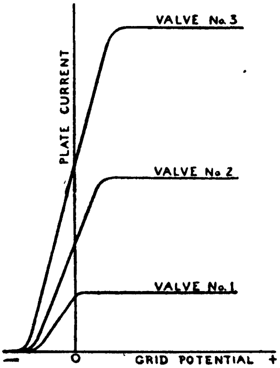


FIG. 115.—Marconi Field Station Receiver, Type No. 38 (*a*). The three Valve Working Characteristics.

No. 2 has a brighter filament, and therefore a steeper characteristic, and positive potentials added to the zero grid increase the plate current along the straight part of its curve.

The filament of No. 3 which is still brighter, causes the valve to have a steeper characteristic than No. 2, with the straight part of the curve extending over a wider range of positive potential.

"Q" type valves are used which normally require about 4 volts across the filament, a 6-volt 40-ampere-hour accumulator is supplied, and an E.M.F. of about 150 volts—obtained from a dry-cell battery—is applied between plate and filament.

Marconi Valve Amplifier, Type No. 55.—This instrument (Fig. 116) consists of a series of six high-frequency amplifier circuits which progressively build up signals, and then deliver them to a rectifier circuit. It therefore makes use of seven valves. The instrument is completely enclosed in an earthed metal case.

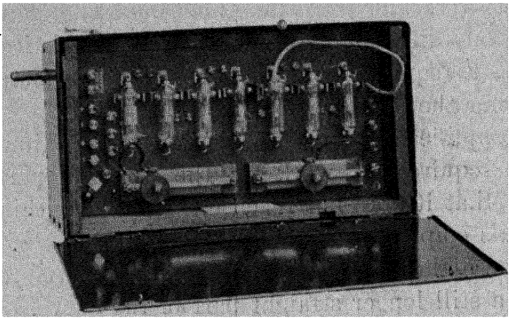


FIG. 116.—Marconi Valve Amplifier, Type No. 55. General View.

Some form of wave selector circuit connected to the aerial must be used with it, which transfers the potential due to the aerial current, to the grid and filament of the first valve.

A transformer is used to convey the amplified signals from the plate circuit of the first valve to the grid circuit of the next. It consists of two windings of very high resistance on an ebonite former, which, besides their magnetic coupling, are also coupled electrostatically by means of a small condenser. Similar connections are used between the second valve and the third, and so on to the grid circuit of the seventh valve. In the last plate circuit is inserted an iron core transformer suitable for conveying rectified and low-frequency impulses to the low-resistance telephone.

The general scheme of connections is shown in Fig. 117.

A connection from the aerial, or selector circuit, is made at the terminal marked A, and from there a flexible lead is clipped on to any one of the amplifying valve grids.

The amplifying valves are marked (a1), (a2), etc., in the order of the amplification they give to the signals before they are rectified.

Rectification takes place in the valve which is not so marked. The coil R, connected to the terminals C, D, is coupled inductively to the plate circuit of valve (a1), and is provided so that a receiver which requires to make use of the reaction effect, can do so by connecting its own reaction coil direct to R, with which it forms an aperiodic circuit.

The rectifier grid circuit can be opened at the terminals FG if necessary, for the inclusion of a transformer, or other device.

A 6-volt accumulator battery, B, is required for the various filament currents, which are regulated by a common series resistance *r*, and a potentiometer P across the same battery allows a common D.C. potential to be applied to all the grids.

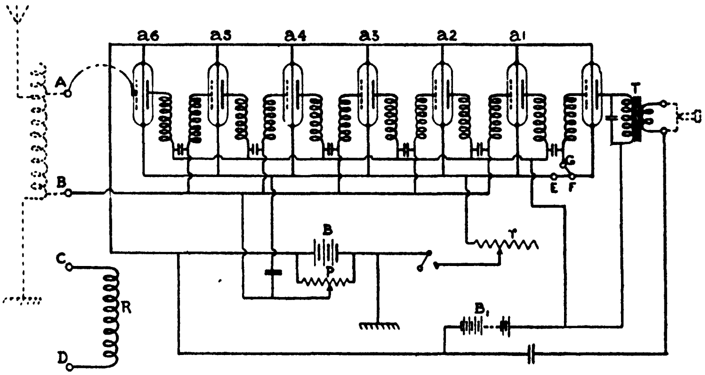


FIG. 117.—Marconi Valve Amplifier, Type No. 55. Scheme of Connections.

The plate currents are taken from a 60-volt dry battery, B_1. The six amplifier valves are known as type V 24, and the rectifier valve as type Q.

The combination of inductance, capacity, and resistance produces a very dead-beat, and almost aperiodic valve circuit—although the windings are so designed that the natural period of each circuit agrees with that of the mean wave-length on which the receiver is required to work. The reaction effects due to leakage, or resistance coupling, or weak inductive, or capacity coupling between the various circuits, which are hard to avoid in a multiple valve receiver, are reduced to a minimum by the absence of iron in the transformers, and the strong damping effect of the resistance windings.

Fig. 118 gives an internal view of the instrument, showing the short, direct method of connection adopted. One of the inter-valve transformers is marked V, the telephone transformer is marked T, and one of the coupling condensers is marked C.

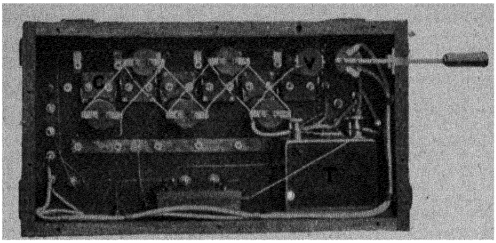


Fig. 118.—Marconi Valve Amplifier, Type No. 55. Internal View of Fittings.

The Multiple Tuner adapted for Use with No. 55 Valve Amplifier.—For financial reasons it is often not advisable to scrap old type receiving apparatus which is still serviceable, particularly if there are means whereby it can be brought up-to-date.

The external connections shown in Fig. 119 will enable spark signals to be received on a No. 55 amplifier receiver, using a standard multiple tuner as wave selector, the change-over switch being in the upper contacts.

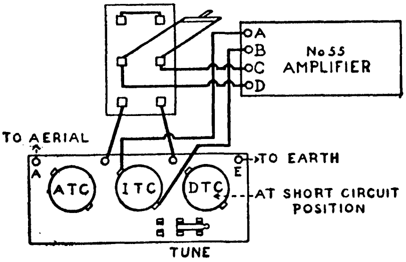


Fig. 119.—Multiple Tuner and Valve Amplifier, No. 55. External Connections.

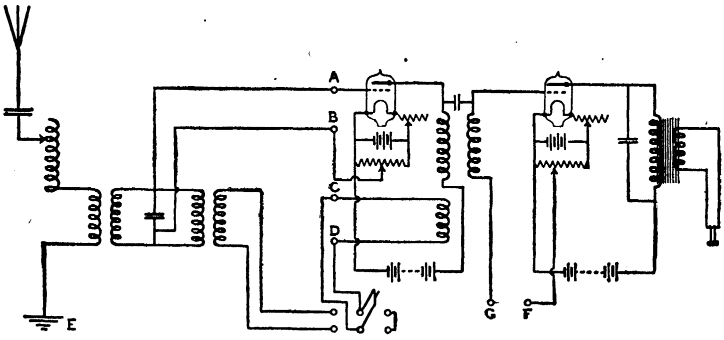


Fig. 120.—Multiple Tuner and Valve Amplifier, No. 55. Internal Connections.

With the switch in the lower contacts, the circuits will be suitable for receiving C.W. signals.

A simplified diagram of the complete arrangement is given in Fig. 120. For the sake of clearness only one amplifying valve, and one rectifying valve, and separate batteries are shown.

It will be seen that in order to receive spark signals the tuner detector circuit is not used. To receive C.W. the coil in the detector circuit is made part of a reaction circuit, being connected to a coil which couples with the plate circuit of the last amplifying valve, the tuner detector condenser being short-circuited.

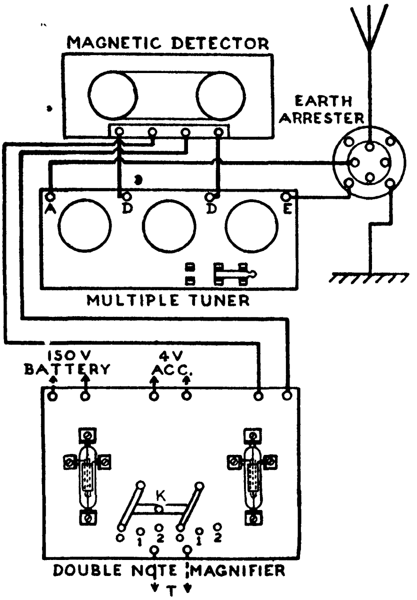


FIG. 121.—Multiple Tuner, Magnetic Detector, and Note Amplifier. External Connections.

Multiple Tuner, Magnetic Detector, and Note Amplifier.—The general lay-out of this circuit is shown in Fig. 121, and a diagram of the internal connections in Fig. 122.

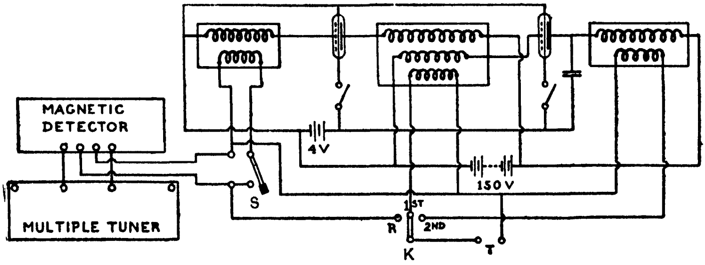


FIG. 122.—Multiple Tuner, Magnetic Detector, and Note Amplifier. Internal Connections.

The switching arrangements allow the rectified signals from the magnetic detector to be either:

(1) Taken direct to the telephone—the switch S being open, and switch K on stop R; or

(2) To be applied to the grid-filament circuit of a valve through an iron core transformer, by closing switch S, and making on the second contact of switch K; or

(3) To be applied to the telephone after two amplifications, the switch K then being on the third contact; a note transformer in the plate circuit of the first valve applying the amplified signal potential to the grid circuit of a second valve, in the plate circuit of which is connected a standard telephone transformer.

Note Amplifier for Use with either Magnetic or Crystal Detector. — The rectifying action of the magnetic detector is a current effect, whereas that of a crystal is a potential effect, the amplifying circuits in the two cases therefore require to be different for best results.

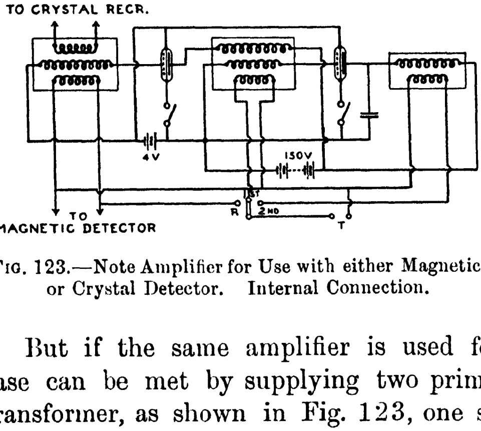


Fig. 123.—Note Amplifier for Use with either Magnetic or Crystal Detector. Internal Connection.

But if the same amplifier is used for either circuit, the case can be met by supplying two primaries to the first grid transformer, as shown in Fig. 123, one suitable for use with the magnetic, the other for use with the crystal.

Marconi Short-Distance Wireless Telephone Transmitter and Receiver.—This instrument, which is illustrated in Fig. 124, comprises the circuits of a continuous-wave valve-oscillator with microphone, forming a wireless telephone transmitter set, arranged in the left-hand portion; and a valve amplifier and crystal detector with the necessary circuits fitted in the right-hand portion.

The aerial tuning inductance used with it is a separate unit.

The transmitter circuits shown in the left-hand part of Fig. 125 are arranged as in Fig. 107, and have therefore been already discussed.

A "T.N." type valve is used, which is fitted with two lime-coated platinum, or plain tungsten filaments, either of which can be connected in circuit by a switch to the 4-volt battery of two 80-ampere-hour accumulators, the working current being about 4 amperes.

A high-tension battery of dry cells supplies from 10 to 15 milliamperes at a pressure of about 500 volts to the plate circuit, through a protective resistance of about 3500 ohms.

A 6-volt 40-ampere-hour battery with an adjustable series resistance in the grid circuit, is used to control the plate current.

The greater filament-plate current output of transmitting valves results in a shorter filament life; they are therefore constructed, some with two filaments, some with three, and with special sockets, so that a change over from one filament to another in the same valve can be conveniently arranged by a suitable plug board, or switch, mounted on the base of the transmitter.

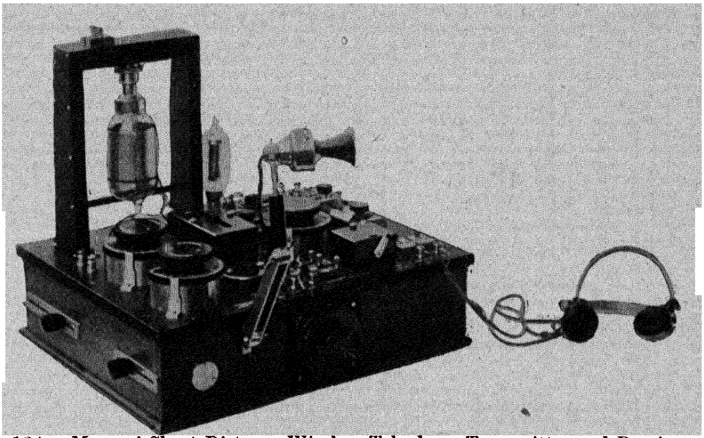


FIG. 124.—Marconi Short-Distance Wireless Telephone Transmitter and Receiver. General View.

" T.N." valves may be termed " soft," as their exhaustion is not carried to a very high degree. This allows the comparatively high-plate current required to be obtained without using a very high-plate voltage.

" Hard " valves, however, are also used, which work satisfactorily with 1200 volts between plate and filament, and carry

30 milliamperes plate current; the aerial current obtained under such conditions being 1·2 to 1·5 amperes.

The receiver circuits, which are shown diagrammatically in the right-hand part of Fig. 125, make use of a "C" type valve as an amplifier, which requires a 6-volt 40-ampere-hour battery, and an adjustable series resistance to regulate the filament current; a 200-volt dry-cell battery for the plate circuit; and an adjustable potential supply for the grid control, which is obtained from a potentiometer P, connected across the filament battery.

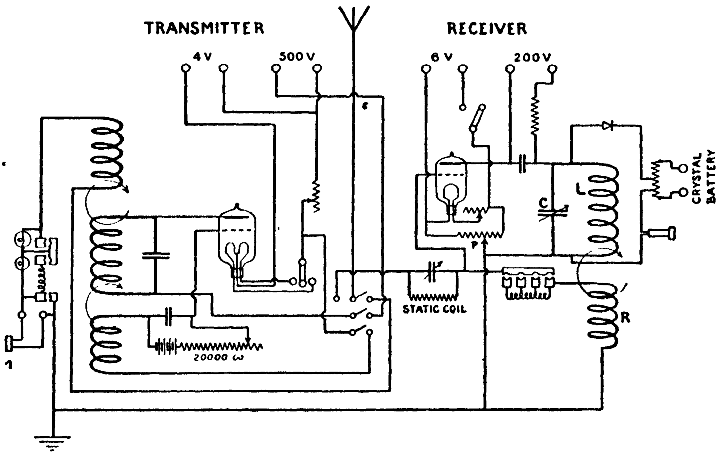


FIG. 125.—Marconi Short-Distance Wireless Telephone Transmitter and Receiver. Internal Scheme of Connections.

In the plate circuit is an inductance coil L, which is tuned to the received wave-length by means of the adjustable condenser C, and across it are connected the crystal and telephones. Another coil R, which is in the aerial circuit, is inductively coupled to L, and with it constitutes a receiving jigger, so that when the valve is not in use signals are conveyed in this way to the crystal.

The valve is brought into play by simply switching on the filament current. The aerial coupling coil R then becomes a reaction coil, and takes energy from the plate circuit to the aerial and grid circuit, and boosts up the amplification.

The external connections of the instrument are shown in Fig. 126.

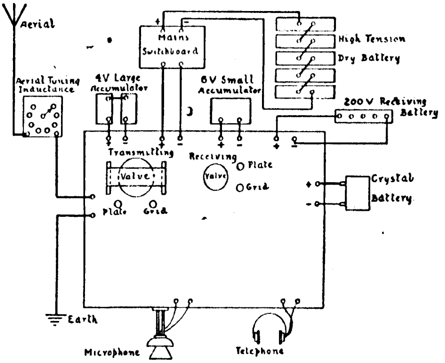


FIG. 126.—Marconi Short-Distance Wireless Telephone Transmitter and Receiver. External Scheme of Connections.

Marconi Short-Distance Wireless Telephone Set, Type T.T. 2.—As in the previous set, the transmitting and receiving circuits are both arranged in one instrument (Fig. 127), which is compact and makes use of small valves. Its internal fitting is shown in Fig. 128, and a wiring diagram in Fig. 129. The change-over switch, Z, completely isolates the transmitting and receiving circuits, and therefore no adjustments are necessary when changing from speaking to receiving. This set is designed to work with a small aerial having a natural wave-length of approximately 250 metres.

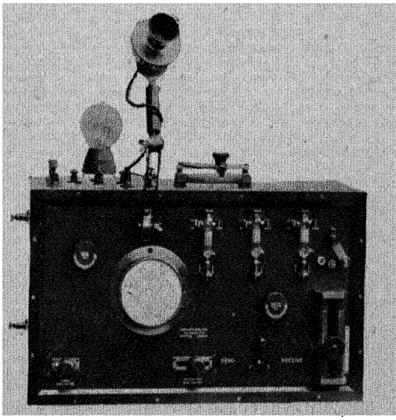


FIG. 127.—Marconi Short-Distance Wireless Telephone Set, Type No. T.T. 2. General View.

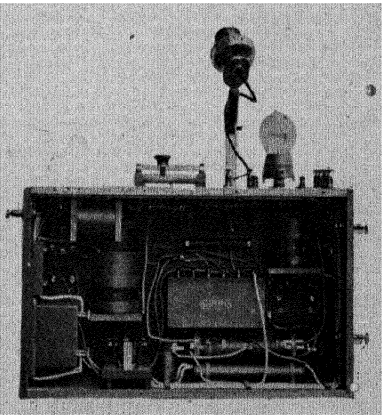


FIG. 128.—Marconi Short-Distance Wireless Telephone Set, Type No. T.T. 2. Internal Fittings.

The transmitting-valve circuit is tuned to 250 metres wave-length exactly, and it is essential, in order to obtain the best results, to tune the aerial circuit to the same wave-length.

Slight adjustment can be made in the aerial circuit by means of the *Aerial Tuning Coil* L_{AT}.

The high-tension supply for the "S" type transmitting valve can be obtained either from a battery or a machine, 750 volts being required. In the event of a machine being used, it may be necessary to place a condenser across its terminals, having a capacity of about 1 mfd., in order to eliminate noises caused through ripples due to commutation, etc.

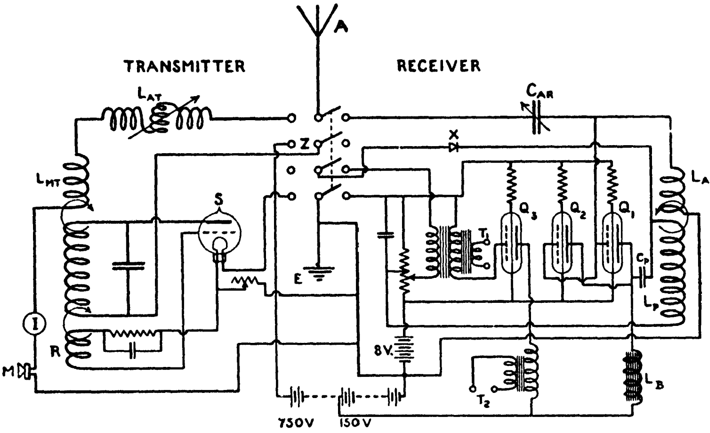


FIG. 129.—Marconi Short-Distance Wireless Telephone Set, Type No. T.T. 2. Scheme of Connections.

The filament current is supplied by an 8-volt 50-ampere-hour battery.

For tuning purposes the microphone terminals, M, should be shorted. On connecting the aerial and earth leads to the instrument and switching on the valve, a reading should be obtained on the aerial ammeter, I. This reading should be brought to a maximum by adjusting the *Aerial Coupling Coil* L_{MT}, and *Reaction Coil* R, and finally by adjusting the *Aerial Tuning Coil* L_{AT}, until best tuning position is obtained.

The microphone, M, can then be placed in circuit ready for speech transmission.

The 8-volt battery is common for both transmitter and receiver valve filaments; the 150-volt high tension required for the "Q" type receiving valves is also supplied from the H.T. battery of the transmitting circuit, a tapping being made at 150 volts.

In the receiver the wave range is approximately 200 to 350 metres. The aerial circuit is tuned to the incoming waves by the sliding condenser C_{AR}, the coil L_{AR} being of fixed inductance, and the strength of signals is regulated by adjusting the *Receiver Reaction Coil* L_{AR}.

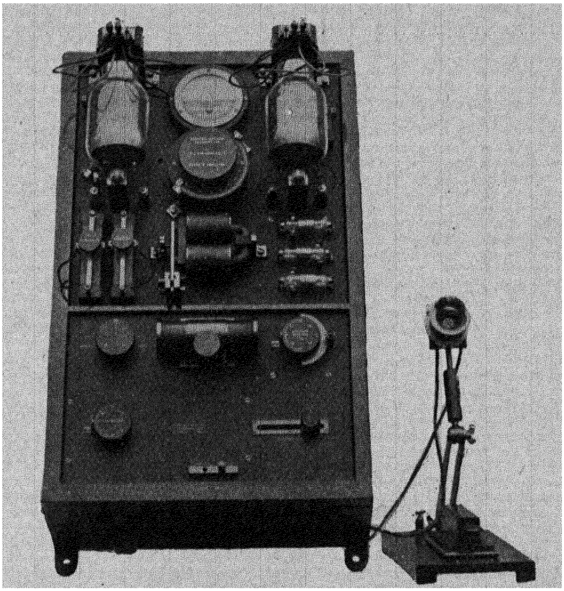


FIG. 130.—Marconi Wireless Telegraph and Telephone Set, Type T.T. 3. General View.

The grids of the two valves, Q_1 and Q_2, are connected in parallel to the aerial circuit between C_{AR} and L_{AR}, so that the potential variations of the aerial oscillations are thereby made to affect the valve plate currents which pass through the highly inductive choke, L_B, from the 150-volt battery.

This same plate battery charges the fixed condenser, C_P, in the fixed but tuned oscillatory circuit C_P L_P, which is completed through the two valves in parallel, and variation of the valve current to the battery starts an oscillation which results in a potential difference across L_P, and this potential difference is applied to a crystal, X. The crystal allows an intermittent rectified current to pass through the primary winding of a transformer, T_1, in series with it, and if no note amplification is required, the telephones are connected to its secondary terminals.

L_P is also inductively coupled to the aerial coil L_{AR}, and the oscillations in it react back on the aerial and strengthen the potential applied to the two grids.

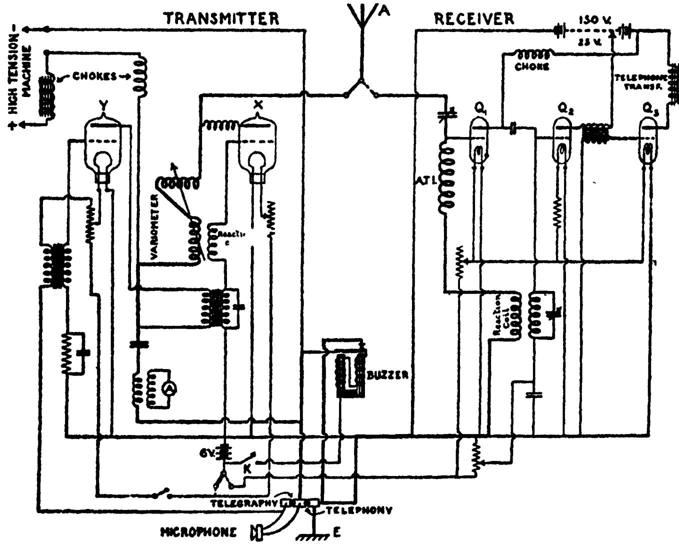


FIG. 131.—Marconi Wireless Telegraph and Telephone Set, Type T.T. 3. Scheme of Connections.

The rectified signals are amplified by means of valve Q_3, a special winding on the transformer T_1 being connected to its grid and filament; and the primary of the telephone transformer T_2 to its plate and filament through the 150 battery.

Marconi Wireless Telegraph and Telephone Set, Type T.T. 3.—The combined transmitter and receiver of this set is shown in Fig. 130, and a simplified diagram of its connections in Fig. 131.

If the microphone is inserted directly in the aerial, the arrangement has the disadvantage that the aerial current is limited to the maximum which the microphone can carry without the carbon granules packing. In the present instrument this limitation is removed.

Two valves are used, one of them—X—being employed to generate continuous oscillations in the aerial; the other—Y—known as the "control" valve, to amplify the microphone speech currents, which are then impressed on the grid circuit of the oscillating valve by means of a suitable transformer, so that the aerial finally receives them after two amplifications.

When the transmitting set is used for telegraphy, the microphone is short-circuited by a plug, and the operator works the key K.

This closes and opens the battery circuit of a buzzer, the contacts of which carry the main aerial current, so that when the buzzer vibrates the C.W. oscillations are broken up into groups by the interruption of the aerial circuit, and the signals are therefore given a note frequency of the same pitch as the note of the buzzer.

The receiver comprises (1) a valve Q_1, which acts as a high-frequency amplifier; (2) a valve Q_2, which acts as a rectifier, having a tunable grid circuit to which is coupled an aerial reaction coil for the production of beat signals; (3) a valve Q_3, which acts as a note amplifier, the receiving telephone being connected through an iron core transformer to its plate circuit.

CHAPTER VI

THE SPECIAL APPARATUS USED FOR HIGH-SPEED TRANSMISSION AND RECEPTION

Transmitting Apparatus.—The Air Compressor and Reservoir.—The Creed Relay and Air Engine.—The High-Tension Signalling Switch.—The Wheatstone Transmitter.—The Wheatstone Perforator.—Dictaphone Reception.—Dictaphone Cylinder Shaving Machine.—The Einthoven Galvanometer Recording Set.—The Marconi-Einthoven Photographic Outfit.

THE problem of high-speed radio working resolves itself into the provision of suitable mechanical means for transmitting signals at a faster rate than is possible by hand key manipulation, and which must also be capable of dealing with the comparatively large operating currents and high voltages used in a spark transmitting set.

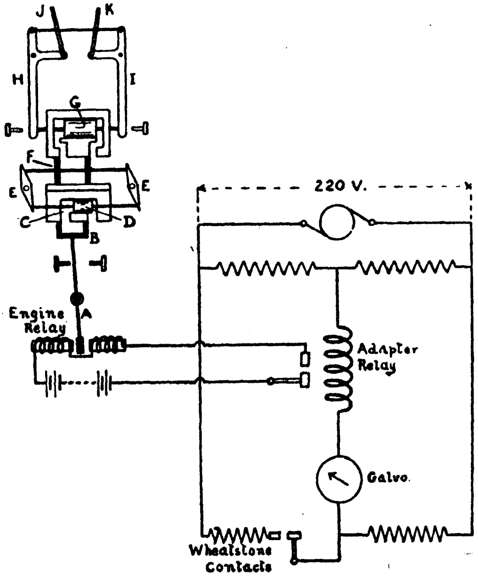


FIG. 132.—Connection Diagram of Wheatstone Transmitter to Creed Air Engine Relay.

Transmitting Apparatus.—As in line telegraphy, the operator punches the message on a tape which is fed into a Wheatstone transmitter. The current which passes through the Wheatstone is made to work a relay (see Fig. 132), which closes the circuit of another relay controlling the supply of compressed air to a Creed air engine, by means of a small " D " slide-valve attached to its armature.

This valve controls a relay engine, which works the valve of the main engine through a system of rocking levers, and finally the main engine, by means of a second system of levers, works the arms of the high-tension transmitting switch controlling the spark discharge (see Fig. 133).

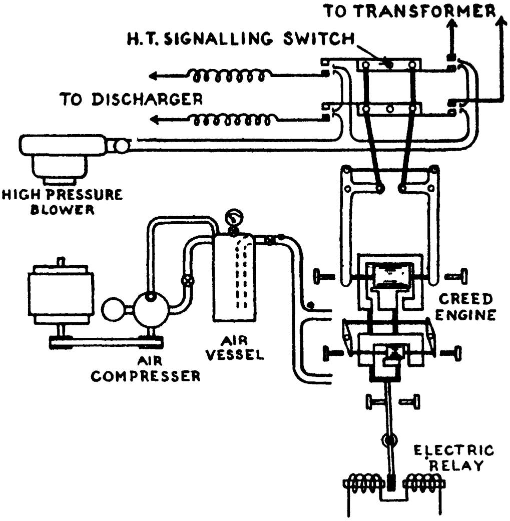


FIG. 133.—General Arrangement of Plant for working High-Tension Signalling Switch at High Speed.

The Air Compressor and Reservoir. — For ordinary working speeds of 100 words per minute, an air compressor capable of taking in 10 c. ft. of free air per minute and delivering it at a pressure of 50 lbs. per sq. inch is required.

Preferably the machine should be air-cooled, as water-cooling necessitates extra fitting and attention.

It is usual to fit an automatic air governor between the air inlet filter and the inlet port, the governor being connected by a copper tube to the reservoir.

When the air pressure in the reservoir, which is indicated by a suitable gauge, reaches the desired value, it overcomes the resistance of a spring controlling a valve in the air governor. This allows the valve to lift from its seating so that air is admitted on to a plunger which closes the air inlet to the cylinder.

The difference in power to the compressor when the air inlet is closed and when open is about 900 watts.

As air under pressure causes condensation of water, it should enter and leave the reservoir from the top, and a cock should be fitted for draining the water off from the bottom.

The outlet pipe, however, should project well down inside the reservoir in order to draw off the coolest air, which is then led through a filter, F (Fig. 134), to the engine.

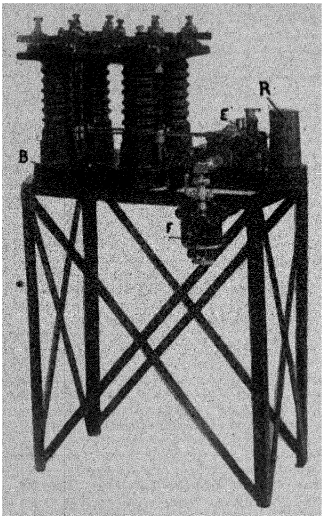


FIG. 134.—View of High-Tension Signalling Switch and Air Engine.

The Creed Relay and Air Engine.—The Creed relay, R (Fig. 134), is of standard pattern and its working current is about 20 milliamperes.

A spacing mark on the perforated tape causes the relay tongue to move in the reverse direction to that obtained when a dot or dash is made.

Fig. 132 illustrates diagrammatically the action of the air engine.

The light, balanced slide-valve B, which is moved by the relay tongue A, controls the supply of air to the cylinder, C, through the two ports, so that the piston, D, moves forwards and backwards in accordance with the signal currents passing through the Wheatstone.

The movements of piston D are communicated by rocking levers, E, to the piston valve of the main engine, F, which controls the double acting piston, G. From each side of this piston a rod projects through the cylinder cover and thrusts in either direction the arms of the three-armed bell-crank levers, H and I.

The rods, J and K, drive the high-tension switch.

The air engine should be kept well oiled and well cleaned between the periods of working, as a certain amount of water accumulates on the various parts, due to condensation.

The High-Tension Signalling Switch.—The engine and switch are mounted together on a cast-iron bedplate, B (Fig. 134).

The high-tension fixed contacts are carried on an ebonite platform supported by four hollow, corrugated ebonite pillars, up which an air blast is conveyed from a centrifugal blower of the type shown in Fig. 135, for the purpose of quenching the arc which occurs on breaking the high-tension current.

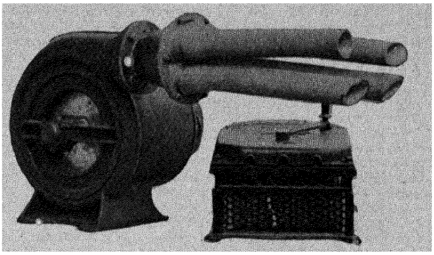


FIG. 135.—Four-Way Motor Blower.

The moving contacts are fixed at the extremities of two strong steel springs, supported by solid, corrugated ebonite pillars fitted for working in ball bearings, and which are driven from the air engine in tandem.

The best working gap for high speeds is about $\frac{1}{4}''$, and each of the four fixed contacts must be most accurately spaced, so that the gaps all open at the same moment.

The Wheatstone Transmitter.—This instrument is shown with its driving motor in Fig. 136.

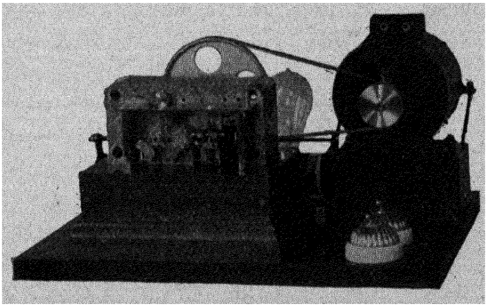
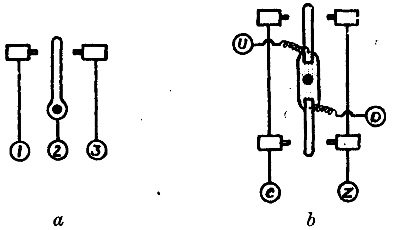


FIG. 136.—View of Wheatstone Transmitter with Driving Motor.

The simplest form has two fixed contacts and one moving contact arm as in Fig. 137 (*a*), while the ordinary type (as used for landline working) has two pairs of fixed contacts and a divided contact arm (Fig. 137 (*b*)). The moving arm is motor driven, its motion being controlled by a moving perforated slip. A short piece of slip is shown in Fig. 138, punched with the word "Marconi." It will be seen that there are three distinct lines of holes running along it. One line of large holes causes a motion of the top of the contact arm to the left, and the other row of large holes a motion to the right. The small holes in the centre engage in the teeth of a small wheel which, on rotating, produces the required motion of the slip.



a *b*

FIG. 137.—Wheatstone Transmitter Contacts.

The method of action of the transmitter is shown in principle in Fig. 139. A rocking piece, A, is moved by means of a crank mechanism, B, which is driven through gearing by a small motor. The rocking piece carries two pins, P_1 and P_2, each of which works a bell crank lever, L_1 and L_2, as shown. Springs S_1 and S_2 hold the lever in contact with the pins. Each lever has attached to it a rod R_1, or R_2, working in a guide G_1, or G_2, and is fitted with an adjustable nut N_1, or N_2, for moving the contact arm C. It will be seen that when P_1 rises, L_1 and R_1 move so that the top of the contact arm moves to the left. Similarly, when P_2 rises, the top of the contact arm moves to the right. Two further rods, D_1 and D_2, are attached to the bell crank levers, and move vertically as shown. The upper ends of these rods come up through small holes to the under side of the slip, each rod opposite one line of the larger holes. Then if a rod comes up at a moment when the movement of the tape brings a hole in line with it, the rod is free to carry out its full motion and the corresponding motion of the contact arm takes place. If, however, the rod meets the paper, its

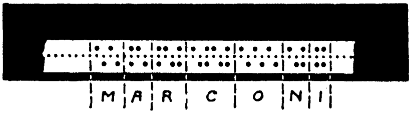


FIG. 138.—Wheatstone Transmitter; Sample of Punched Slip.

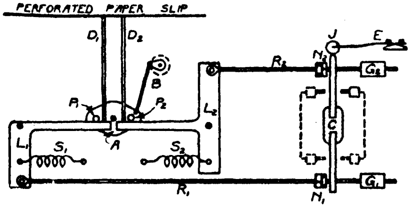


FIG. 139.—Wheatstone Transmitter; Method of working.

upward motion is arrested and so the contact arm is not moved.

The jockey wheel, J, held against the top of the contact arm by the pressure of the spring, E, gives a bias to the motion and also serves to ensure a firm pressure between the arm and the fixed contacts.

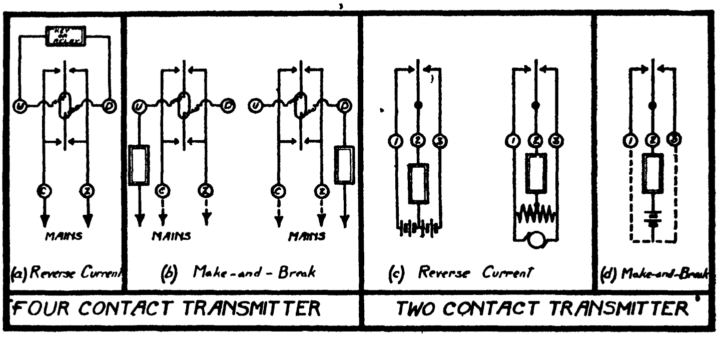


Fig. 140.—Wheatstone Transmitter ; Connection Diagrams.

The connections required will vary according to whether the transmitting gear is being operated by a simple make and break action, or by reversed currents. Fig. 140 shows the connections diagrammatically.

Suitable resistances must be inserted where required, so that the sparking at the contacts is not excessive. The maximum current through the contacts should not be more than about 100 milliamperes. Any adjustments required can be made on the nuts, N_1 and N_2, and also on the fixed contact screws, suitable tools being supplied by the makers for this purpose.

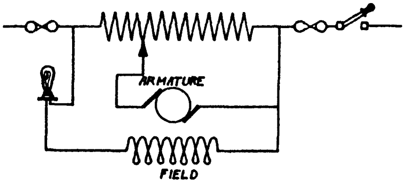


Fig. 141.—Wheatstone Transmitter ; Motor Control Diagram.

The connections for the motor are as shown in Fig. 141.

Wheatstone Perforator.—This appliance (Fig. 142) is used for perforating the slip for use in the Wheatstone transmitter. The principle of its action is illustrated in Fig. 143. Two flat steel plates, A and B, are separated by packing pieces at the top and bottom edges, thus forming a very narrow vertical chamber through which passes the slip to be punched. Holes *a, b, c, d,* and *e* are provided right through both plates, as shown in the figure, and in each hole works a punch. The punches are actuated by three bell crank levers, C, pivoted at D, a plate, E, being provided on each lever, the three forming the keyboard seen in Fig. 142. The punches are normally held out of the holes by means of spiral springs. On pressing the left-hand plate ("dot"), punches operate in holes *a, b,* and *d*; the middle plate ("space") works punch *d* alone, and the right hand plate ("dash") operates *a, c, d,* and *e.* On releasing each plate, a ratchet gear moves the slip forward by the required amount—one space for a dot, and two spaces for a dash. When inserting slip for perforating, this feeding gear must be released by pulling forward the small lever at the left-hand side of the mechanism case.

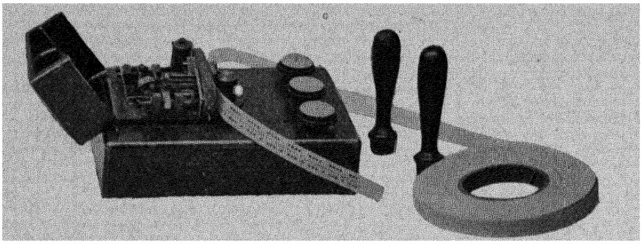


Fig. 142.—View of Wheatstone Perforator.

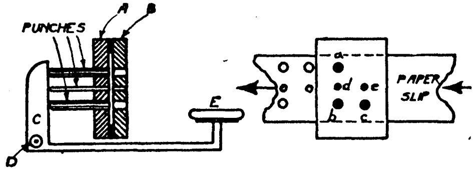


Fig. 143.—Wheatstone Perforator; its Principle of working.

Two wooden punching handles fitted with rubber cushions are used to manipulate the perforator, which requires a good firm punch to obtain certain action.

Two slips may be perforated at once on one of these hand-manipulated machines, though pneumatically operated machines are made which will punch up to eight slips simultaneously. Other types of perforators are made with keyboards similar to an ordinary typewriter.

Dictaphone Reception.—The recording of incoming signals on dictaphone cylinders has four uses. In the first place it will allow of one person—not necessarily a skilled operator—recording signals which can be read off at any convenient time by an operator. Secondly, it will allow of one operator working several receiving sets at rush periods, the cylinders being run off and transcribed when convenient. Thirdly—and this is its most important use—it allows of the reception of high-speed signals. Fourthly, it allows of a permanent record being made of important messages.

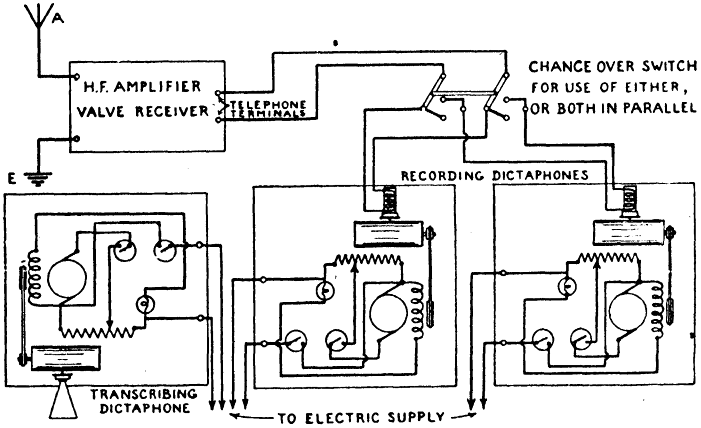


FIG. 144.—Connection Diagram for Dictaphone Reception.

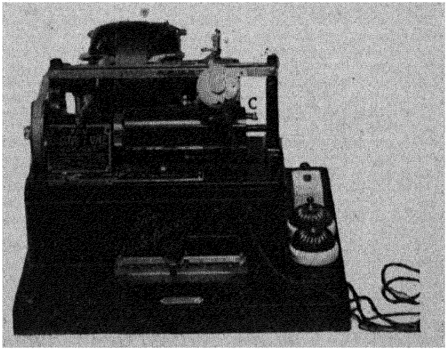


FIG. 145.—View of Dictaphone.

Fig. 144 shows a valve receiver—which should include one or more amplifier circuits—connected at its telephone terminals to a dictaphone recorder set, and Fig. 145 a dictaphone instrument.

The method used for receiving high-speed signals is to run the *recording* dictaphone cylinder at a high speed, the *transcribing* from the cylinder being subsequently done at a much lower speed. This has the effect of reducing the speed of the signals in direct proportion to the reduction in speed of the dictaphone cylinder in the two operations. For example, suppose signals are coming in at 100 words per minute and the recording dictaphone is run at 400 r.p.m. If, again, the transcribing dictaphone is run at 100 r.p.m., then the effective signal speed for the transcribing operator will be $100 \times \frac{100}{400} = 25$ words per minute. It should be noted, however, that this will reduce the note very considerably, and so for reception at high speeds a fairly high note is necessary for the incoming signals. It is hardly necessary to mention that the signal current passed into the dictaphone must be as strong as possible. The recording and transcribing dictaphones can be either the same or separate instruments, depending on the service conditions, also on the type of dictaphone—some dictaphones being arranged to fulfil both purposes and others only one. The dictaphones are driven by an external belt-connected motor, the speed of which is controlled in exactly the same way as the motor for the Wheatstone transmitter (see Fig. 141).

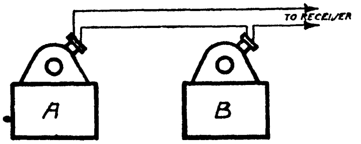


FIG. 146.—Two Dictaphones with Telephones connected in Series.

To avoid having to change cylinders in the middle of a message it is usual to have two recording dictaphones with their telephones in series as shown in Fig. 146. Suppose a message commenced on dictaphone A has to be continued on B, then B must be started moving *just before* dictaphone A finishes, so as to get some overlap and so ensure correct transcription.

Coming to the details of the machines, the transcribing dictaphone is simply a phonograph fitted with a special pneumatic telephone arrangement in place of the usual horn. Instead of the usual replaceable steel needles the dictaphone is fitted with a permanent jewel. The recording dictaphone only differs from the transcribing machine in having a fairly sharp "needle" pressing very lightly on the wax cylinder, instead of the more rounded needle held on by a spring pressure which is provided for the transcriber. The recorder mouthpiece is adapted to take a special telephone earpiece connected to the receiving set. Some dictaphones have a combination arrangement whereby either a recording mouthpiece (marked "Speak Here") or a transcribing earpiece (marked "Listen Here") can be brought into use.

The following points should be noted when using the dictaphone:

(1) To place a cylinder in position raise the needle carrier so that the needle will clear the cylinder, slip back the end catch ((*c*) Fig. 145) on the drum, and push the cylinder in position. That end of the cylinder which has the larger diameter central hole must of course go on first. Finally, slip end catch into position again, run carrier along to the left-hand end of the cylinder, and drop it down into position. Care must be taken not to handle the *surface* of the wax cylinder.

(2) To remove the cylinder, lift the needle carrier, slip back the catch, and pull over the handle, H (Fig. 145), sharply to the right, taking care that the cylinder does not shoot right off the drum and break.

Dictaphone Cylinder Shaving Machine.—This machine consists of a motor-driven drum for rotating the cylinders, and a razor blade having a longitudinal motion and an adjustable feed. The motor resistance is set at a value giving a suitable cylinder speed at the given supply voltage, and should not be altered except when the voltage is changed. The chief point to be kept in mind when cleaning cylinders is to take a number of fine cuts rather than one heavy cut; this will ensure a much smoother surface.

The Einthoven Galvanometer Recording Set.—The Einthoven String Galvanometer is described on page 171. Its essential parts are (1) a single straight stretched conducting fibre, and (2) a powerful electromagnet, which deflects the fibre, or string, when it is carrying current.

The string may be of low or high resistance, and the sensitivity of the instrument varies accordingly, but it can be made to detect currents as low as 10^{-12} ampere, and to work on frequencies up to 200 cycles.

In order to record Wireless Signals, the string is connected in series in the rectifier circuit. The highest sensitivity is not required, but it must respond in a dead-beat manner to the frequency of the dots and dashes of high-speed working.

The string is arranged to act as a shutter in a camera, either opening or closing by its movement a small hole which allows a beam of light to fall on a travelling strip of sensitised paper, or else to vary its position in front of a narrow transverse slit, which allows the complete movement of one part of the string to be recorded.

Fig. 147 shows in diagram the galvanometer optical system

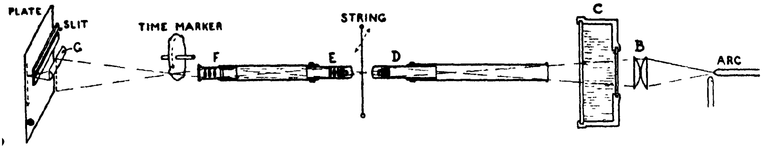


Fig. 147.—Einthoven Galvanometer Recording Set; the Optical System.

supplied by the Cambridge Scientific Instrument Company, a short description of which is as follows:

The string is powerfully illuminated from the positive crater of an arc, the light being concentrated by condensing lenses at B and D, while a water bath is interposed at C, to absorb the heat rays and so to protect the lenses at D, and to prevent the string from being heated.

The field of the objective E passes through the eyepiece F, and is projected on to a cylindrical lens G, which focusses part of it into an intensely bright band of light in the plane of the sensitised plate or paper.

The string appears in front of the lens as a long vertical shadow about a millimetre wide, the part overlapping the cylindrical lens becoming a dark spot in the line of light which falls on the plate.

Then, if the plate or paper is given a motion at right angles to the cylindrical lens, the whole length will be in turn exposed, except that portion which is hidden by the shadow of the string; and as the movements of the string are parallel to the length of the cylindrical lens, and each instantaneous position is indicated by an unexposed spot, a continuous series of such spots, forming a line record, is produced on the moving plate or paper.

Fig. 148 shows an Einthoven galvanometer with optical system, fitted to a Marconi photographic cabinet, the doors of which have been removed.

By means of a system of large pulleys which are belt-driven from the motor M, the sensitised paper, or linen tape, is run off the drum H, in front of the slit where it is exposed to the arc light, thence round a system of small pulleys which carry it through a number of developing and washing baths, and finally over a drying band X, and out of the cabinet.

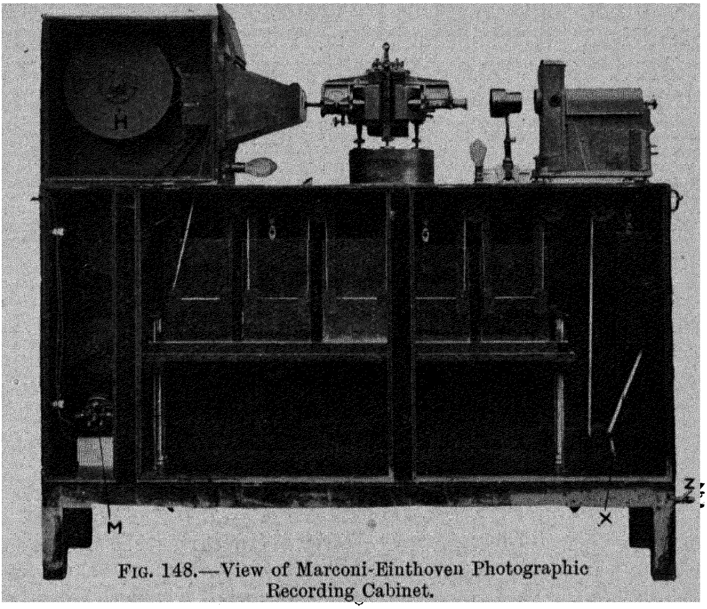


Fig. 148.—View of Marconi-Einthoven Photographic Recording Cabinet.

The baths are carried on a tray which can be lowered by turning a handle, which is partly shown at Z, when it is necessary either to fit a new tape or for any other reason to withdraw the pulley mechanism from the baths.

CHAPTER VII

THE MEASUREMENT OF ELECTRIC CURRENT, AND OF ELECTROMOTIVE FORCE

The Unit of Current.—The Kelvin Balance.—Galvanometers.—"Factor of Merit."—The D'Arsonval Type.—"Dead-beat" and "Ballistic" Movements.—The Thomson Astatic Galvanometer.—The Thermo-Electric Effect.—The Duddell Thermo-Galvanometer.—The Duddell Oscillograph.—The Drysdale-Tinsley Vibration Galvanometer.—The Einthoven String Galvanometer.—The Measurement of Electromotive Force.—The Definition of the Volt.—The Clark Cell.—The Weston Cadmium Cell.—The Potentiometer.—Its Adjustment.—The Measurement of P.D. across a Resistance.—The Calibration of an Ammeter; of a Galvanometer; of a Low-Tension Voltmeter.—Commercial Potentiometers.—The Quadrant Electrometer.—The Original Thomson Instrument.—The Dolezalek Electrometer.—The Measurement of High Potentials.—Current and Potential Indicating Instruments.—Ammeters.—Voltmeters.—Similarity of Design.—The Division of Electromagnetic Instruments into Three Groups.—The Moving Coil Principle.—The Average Current Indication.—The Dynamometer Principle.—The R.M.S. Current Indication.—Soft Iron Ammeters.—The Everett-Edgecombe Model.—The Weston Model.—Thermo-Ammeters.—The Hartmann and Braun Hot-Wire Type.—Methods of increasing the Current-carrying Capacity of the Expanding Wire.—A Hartmann and Braun so-called "Shuntless" Ammeter.—The Duddell Thermo-Ammeter.—Parallel Wire Ammeters with Thermo-Junctions.—The Marconi-Ewen Ammeter for Small Currents.—The Marconi-Ewen Ammeter for Heavy Currents.—Air-Core Current Transformers.—The Electrostatic Voltmeter.—For Medium Voltages.—The Kelvin Volt Balance.

The Measurement of Electric Current.—The practical unit of current is the "ampere," and is defined as that current which when passed through a neutral solution of nitrate of silver containing 15 parts by weight of the salt to 85 of water, using a silver anode and platinum cathode, deposits silver at the rate of 0·001118 of a gramme per second.

The best form of instrument to act as a Test Room Standard Amperemeter is one which acts, however, on electro-dynamic and not chemical principles, such as the Kelvin Balance, by means of which the pull resulting from the attraction between like currents, and the push resulting from the repulsion of unlike currents, is actually weighed.

Thus in Fig. 149 there are two movable coils marked M, which swing on a suspension at P, between four fixed coils marked F, with which they are connected in series. They are all wound in such a manner that the resultant attraction between coils in which the current moves in the same direction, assists the repulsion between coils in which the current moves in opposed directions, so that one M coil is pulled up and the other M coil down. Suppose now the movable arm is adjusted to a mid-position of equilibrium between the F coils, then let a weight be added to a scale pan at W, so that the lever swings down on that side. If now a current is passed through the coils so that the lever lifts again into the mid-position of equilibrium, the weight used will be a dynamic measure of the current flowing. In practice, of course, the current is of a given value, and the weight—or rather the mechanical couple produced by it on the lever—must be varied to measure it.

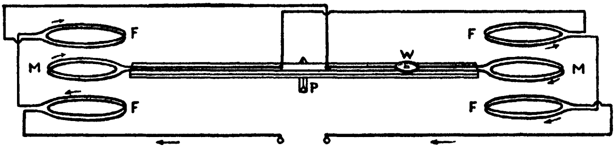


FIG. 149.—The Kelvin Ampere Balance : Principle of Action.

Thus in Fig. 150, when there is no current flowing, a standard weight, W, fixed on a carrier at the zero position on the scale at one end of the lever, is balanced by a counterpoise in the V-shaped pan V, at the other end of the lever, so that the moving coils float in the mid-position of equilibrium as shown by the index, X.

When a current flows, the counterpoise end of the lever moves up, and the standard weight must then be moved from its zero position along the slide on the scale until the index again returns to its mid-position. The current strength is then proportional to the square root of the distance moved by the weight to restore equilibrium.

For true accuracy, an instrument of this character, which depends on the weight of a given mass, requires to be corrected for the acceleration of gravity, which varies with latitude and height above sea-level.

The general checking and calibration of commercial ammeters and the accurate measurement of current for many other purposes is, however, best done on the potentiometer, when, by using a standard of electro-motive force, the fall of potential down a known standard resistance in series with the ammeter is measured, and the current through the ammeter is then calculated.

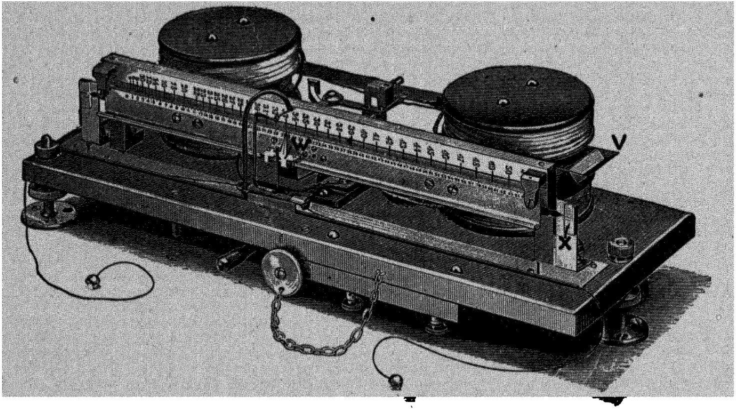


FIG. 150.—View of Kelvin Ampere Balance.

Galvanometers.—Instruments which measure the magnitude or sense of electric currents may all be included under the general heading of galvanometers, but the term is more especially reserved for instruments of high sensitivity suitable for measuring the magnitude of minute currents.

The essence of their construction is, (1) a moving coil and a fixed magnet, as in the D'Arsonval type, or alternatively, (2) a moving magnet or magnets, and a fixed coil or coils, as in the Thomson astatic type.

Sensitivity depends to a large extent on (*a*) the intensity of the field due to the magnet system, and (*b*) the number of turns in the coil; but in order to obtain a fair comparison between the sensitivities of different galvanometers for a given current, the periodic time of the moving system—and therefore its *inertia*—should also be taken into account. This can be expressed by the "Factor of Merit" of the instrument, thus

$$E = \frac{100 \times D}{T^2 \times R^{\frac{2}{5}}},$$

where E = Factor of Merit,
D = Deflection in millimetres per micro-amp. at a scale distance of 1 metre,
T = Periodic Time (undamped) in seconds,
R = Galvanometer Resistance in ohms.

The D'Arsonval Galvanometer (Fig. 151 (*a*)), which is in very general use, more especially for nul or balanced current methods of testing—the Wheatstone bridge circuit being a typical case—consists of a light moving coil surrounding a fixed iron core, and suspended between the poles ot a strong permanent magnet. The coil carries a small mirror, and its movement is controlled by a spring.

A beam of light is concentrated on the mirror and is reflected on to a scale divided in millimetres, which is usually set at one metre distance from the mirror. The current to be measured is passed through the coil and the deflection of the spot of light on the scale is noted.

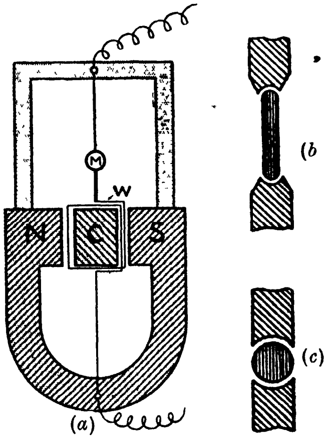


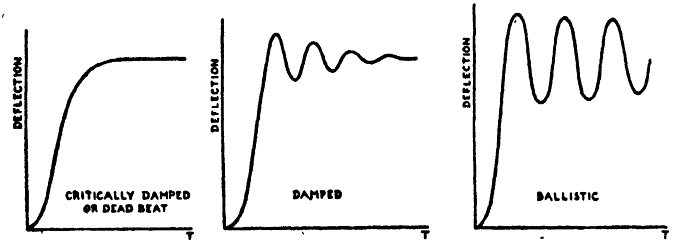
FIG. 151.—(*a*) The D'Arsonval Galvanometer. (*b*) and (*c*) The Shape of its Magnet Poles.

A zero pattern D'Arsonval will have its poles shaped as shown in Fig. 151 (*b*), in order to apply a concentrated field on the coil at its position of rest; a D'Arsonval for measuring current by proportional deflection will have poles shaped like Fig. 151 (*c*), so as to provide a radial field of very nearly equal intensity throughout the working arc of movement of the coil.

"Dead-beat" and "Ballistic" Galvanometers.—When measuring steady currents it is the final deflection which is required, and a galvanometer is therefore employed which takes up its final deflectional position very quickly, that is, after one or two swings. To act in this way, it must have a high *damping factor.*

Air and oil damping are often used for this purpose, and the moving coil is generally encased in a cylinder of non-magnetic metal. When the coil is deflected, the cylinder traverses the magnetic field, and currents are induced in it which exert an opposing torque tending to bring the coil to rest.

Fig. 152 (*b*) shows the character of the scale reading obtained under such conditions; I, being the value of current as finally indicated by steady deflection.



(*a*) (*b*) (*c*)

FIG. 152.—The Damping of Galvanometer Movements.

There are some tests which require that the swing of the galvanometer shall not pass the point of deflection for the given current, as indicated in Fig. 152 (*a*). The movement is then said to be "critically damped," or "dead beat." Sometimes these terms are used to describe a movement which gives just one oscillation beyond its final deflection, and if it does not pass beyond it the movement is said to be "aperiodic."

Again there are other tests, as in the case of measuring the discharge of a condenser, when it is the amplitude of the first throw which is of importance, and in that case the coil must be allowed to swing as freely as possible with minimum damping, as is indicated in Fig. 152 (*c*). A galvanometer with this sort of movement is said to be "ballistic."

The Thomson Astatic Galvanometer.—An "Astatic" system is an arrangement of coils, or magnets, such that the effect of an external magnetic field—whether due to the earth or other coils or magnets—on one part of the system, is equal to, and balanced by, its effect on another part of the system, so that the resultant effect is zero.

The astatic system of a Thomson galvanometer is illustrated in Fig. 153.

A suspension of quartz fibre, AB, carries eight small magnets, or needles, four of which are cemented on at C, and four others at D, the two systems being in the same plane but with their opposite poles immediately under each other.

Each system is at the exact centre of a coil which carries the current to be measured.

A mirror, M, is arranged either at the middle, or at the bottom of the suspension.

Two overhanging bar magnets, whose orientation and distance from the needle systems can be altered, provide a local controlling field which is able to bring the suspension system to zero, and to alter the sensibility of the galvanometer.

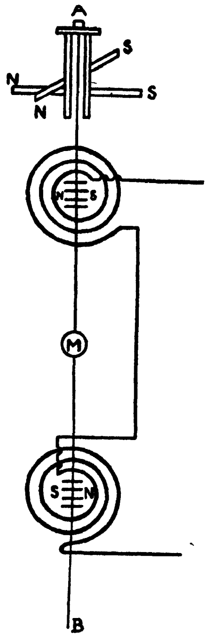


FIG. 153.—The Thomson Astatic Galvanometer.

The Thermo-Electric Effect.—When two different metals are brought into contact, an E.M.F.—which may be very minute—is generated at the contact surfaces.

If the metals are in the form of wires and their common junction is heated, the free ends being kept cool and connected to a galvanometer, a flow of current can generally be detected; and the E.M.F. which gives rise to the current bears a certain definite relation to the heat applied.

A two-wire unit employed in this manner is called a *thermo-couple*, or *thermo-junction*.

If lead is used as the standard metal for comparison, and wires of other metals are connected to form junctions, the thermo-electric power developed with increase of temperature is shown in Fig. 154.

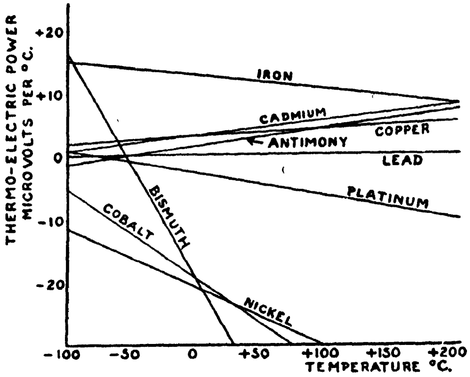


Fig. 154.—The Thermo-Electric Power of Various Metals.

The Duddell Thermo - Galvanometer.—The above principle is applied in this galvanometer (Fig. 155), in the following manner.

A single loop of fine silver wire A, which terminates in a bismuth-antimony thermo-junction, is suspended by means of a glass stem G, carrying a mirror M, from a fine quartz fibre Q, between the poles of a permanent magnet NS.

The current to be measured is passed through the fine wire heater H, which is mounted close underneath the thermo-junction.

A current is generated in the silver loop proportional to the heat received at the junction, and therefore proportional to the square of the current passing through the heater.

The loop current reacts with the permanent magnetic field, with the result that the loop is deflected and the light beam from the mirror gives a scale reading.

The special advantage of this galvanometer is that it can be employed to measure very small direct, or alternating, or high-frequency currents with almost equal accuracy.

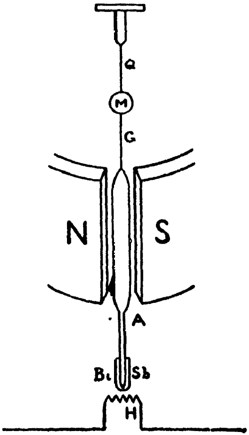


Fig. 155.—The Duddell Thermo-Galvanometer.

The Duddell Oscillograph Galvanometer.—This is another moving coil galvanometer in which the coil consists of a loop of one turn. The instrument is designed to follow accurately the rapid changes which take place at every instant in an alternating current.

The current causes the loop to twist first one way, and then the other way as its direction is reversed, with the result that a circular light beam reflected from the galvanometer mirror will not produce a spot on the scale, but a bright line, having a maximum length proportional to the amplitude of the current flowing.

If the scale is now replaced by a mirror which revolves at a fixed speed in a direction at right angles to the movement of the reflected beam, the instantaneous deflections of the loop with reference to its point of rest will be shown in the mirror as a bright curve fluctuating about a zero line. A *current wave-form* of this nature can be recorded by replacing the mirror by a sensitised plate, which is dropped through the light beam in a direction at right angles to the beam's motion.

It is obvious (1) that the natural period of vibration of the moving part must be very much shorter than any electrical vibration to which it may be required to respond; and (2) it must be critically damped—see Fig. 152 (*a*),—in order to give a clear-cut deflection at every instant proportional to the instantaneous value of the current flowing.

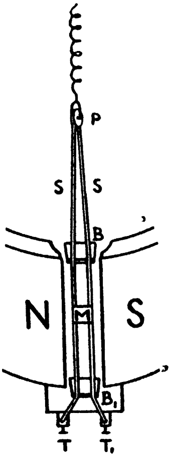


FIG. 156. — The Duddell Oscillograph Galvanometer.

These conditions are obtained (*a*) by using a fine strip of phosphor bronze, SS (Fig. 156), bent back on itself round a pulley P, with its two ends in clamping terminals T T_1, the two legs of the loop so formed, being held in even tension by a spring adjustment supporting the pulley, and the vibratory portion being limited by bridges B B_1 to the part immediately in the magnetic field;

(*b*) by immersing the whole of the "vibrator"—as the above complete fitting is called—in an oil bath.

The mirror, M, is fixed to both legs of the loop at the centre of the vibratory part.

The natural period of the loop is $\frac{1}{10000}$th of a second, and owing to the high damping, it gives accurate deflection without distortion for current periodicities up to 300 per second.

Vibration Galvanometers.—The instrument just described can be greatly increased in sensitivity (1) by working the loop in air instead of in oil, and in other ways reducing the damping on its vibration to a minimum; also (2) by employing it on an alternating current supply which has the same frequency as the natural rate of vibration of the loop, so that the resonance principle is employed to increase its amplitude.

It then becomes a Duddell "Vibration Galvanometer," an instrument which is extremely sensitive to small A.C. currents, so that it can be used in A.C. potentiometer, or in capacity bridge, or inductance bridge circuits, where nul methods of testing are employed. When the circuits are out of balance, an alternating current flows through the galvanometer, and the light beam reflected from the mirror shows as a band on the scale. This band reduces to a stationary spot when the circuits are in balance.

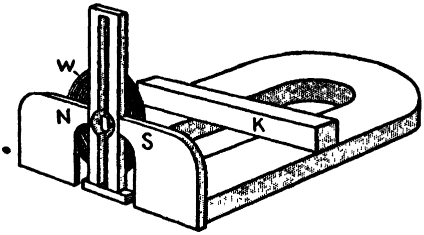


FIG. 157.—The Drysdale-Tinsley Vibration Galvanometer.

The vibrator may consist of a moving magnet, as in the Drysdale-Tinsley instrument (Fig. 157). A small soft iron needle, which carries the mirror, is suspended between the poles of a permanent magnet NS, and is influenced by the field of the current to be measured which passes through the coil W.

The natural period of vibration of the magnetised needle is determined by the strength of the constraining field, and this can be adjusted to agree with that of the alternating current by altering the position of the keeper K, on the limbs of the permanent magnet.

The Einthoven String Galvanometer.—This instrument is designed to have the maximum sensitivity to weak currents which it is possible to obtain in practice.

The two factors, T and R, in the expression for E, the "Factor of Merit" of a galvanometer (see p. 165), involve the inertia and size of the moving coil, and Einthoven has demonstrated that

$$E \propto \frac{1}{d \times \sqrt{t}},$$

where t = number of turns, and d = diameter of wire, so that the greatest sensitivity will be obtained when the coil has the least number of turns and the wire used has the smallest diameter.

Einthoven employs only part of a turn, a single stretched conductor, the diameter of which has been reduced to a minimum by using a very fine glass fibre of about 0·002 mm. diameter, coated with silver.

The fibre is mounted in a narrow air-gap between the poles of a strong electro-magnet, the magnetic circuit being highly saturated so that small changes in the current through the exciting coils make a negligible difference to the flux.

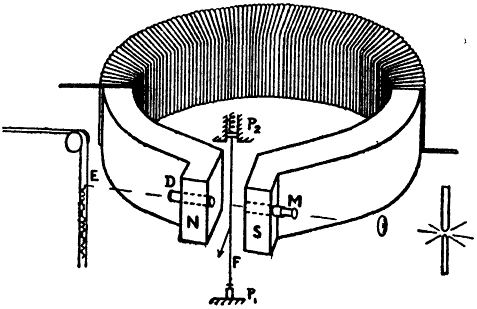


FIG. 158.—The Einthoven String Galvanometer.

In Fig. 158 the silver-coated fibre, F, is soldered at one end to a fixed plate P1, and at the other to a plate with a spring tension adjustment working in a guide, at P2.

The movement of the fibre is indicated by the arrow; that is, it is transverse to the direction of the magnetic field, and also to the direction of the current.

Observation of this movement is provided by a microscope M, which is fitted in a sighting-hole bored through one of the poles, the hole being extended through the other pole for projection purposes. To obtain a photographic record, suitable lenses are fitted at M and D; the fibre is illuminated by means of an arc lamp, and a small portion of its shadow is projected on a sensitised plate, or paper ribbon, fixed at some position E, the wavy line on the tape representing the sort of record which would be obtained after photographic development, if a varying current were passed through the galvanometer.

The normal tension adjustment on the finest fibre employed gives it a period of about $\frac{1}{200}$th second. Its weight is approximately 10^{-6} grams, resistance 10,000 ohms, and the smallest current it will measure of the order of 10^{-12} amperes. Heavier fibres with resistance as low as 5 ohms—which of course are far less sensitive—are often used for larger currents.

An Einthoven galvanometer is occasionally used in radio-telegraphy for recording signals (see p. 159), in which case it would be connected in series, in the rectifier circuit.

The Measurement of Electromotive Force.—The standard practical unit, the "volt," is defined as that value of unvarying E.M.F. which creates in a circuit having a resistance equal to one ohm, an unvarying current of one ampere. But for many purposes it is more convenient to have a standard E.M.F. available which does not necessitate the measurement of a current through a standard resistance, which is obtained instead as a constant potential difference between two terminals. This has led to the development of various forms of a standard voltaic cell, the earliest of which, the Clark cell, made use of the elements mercury, zinc sulphate paste, and zinc, with platinum wires from the mercury and zinc to the terminals, giving 1·434 volts at 15° C., while the one now in most general use, the Weston cadmium cell, which has a temperature coefficient so small that it is negligible for nearly all tests, makes use of mercury, mercurous sulphate, cadmium sulphate, and cadmium, connection to the electrodes being made as before by platinum wires. A section through the cell is shown in Fig. 159. Its E.M.F. is 1·0198 volts, which remains constant for years provided no current in excess of ·0001 ampere is taken from it.

Having given a standard cell providing a standard E.M.F., a measurement of any value of steady potential difference can be made by means of the "Potentiometer," one of the most useful standardising instruments in the Test Room.

In its simplified form the potentiometer circuit is as shown in Fig. 160. It consists essentially of a wire, AC, having a uniform resistance throughout its length, stretched over an evenly divided scale of say 2000 parts, and connected to a battery, B, of two accumulators through a regulating resistance *r*.

By means of a sensitive D'Arsonval galvanometer G, and a standard cell S, the right value of *r* is found which adjusts the fall of potential from A to C due to the current from B, to 2 volts—that is, to ·001 volt per division. This operation is carried out as follows: The galvanometer and standard-cell circuit is connected at A to the zero on the scale, and by a slider, E, to that scale-reading which is 1000 times the voltage of the standard cell; thus if a Weston cell is used—to 1019·8 on the scale. Then, the standard cell being so connected as to oppose the battery B, the resistance *r* is altered until the galvanometer shows no deflection. When this balance is obtained, the potential difference between A and E due to B, is equal to the P.D. due to S, that is to the scale-reading at E. The drop is then equal to ·001 volt per division, or 2 volts over the full scale of 2000 divisions.

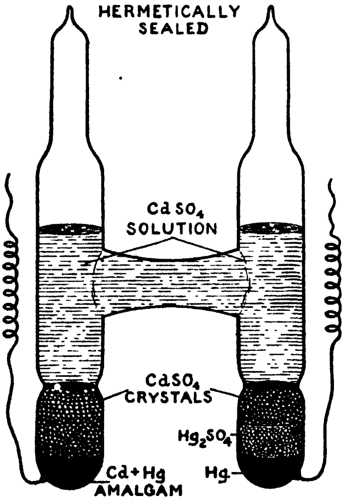


FIG. 159.—The Weston Cadmium Cell.

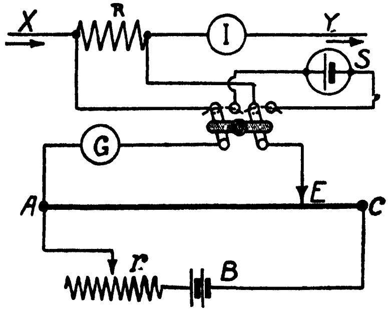


FIG. 160.—Simple Potentiometer Circuit.

Thus adjusted, or "set," the potentiometer may be used to measure any other potential difference—such as the drop across R when a steady current of unknown value flows through it—by substituting potential connections from R for the standard cell in the galvanometer circuit, taking care, as before, that the potential current flows in opposition to the potentiometer battery current, and then altering the position of E until the galvanometer by giving no deflection shows that balance is once more obtained, when the scale position of E will then indicate the drop across R. R being known, it is then possible to calculate the current in the circuit XY, and if necessary to calibrate an ammeter, AM, by inserting it in series in the XY circuit together with an adjustable resistance, not shown, for altering the value of current through XY.

To calibrate a galvanometer by potentiometer (Fig. 161), first "set" the potentiometer by means of the standard cell, then switch the galvanometer off the cell and on to a high resistance, R, of such a value that the connection of this resistance and the galvanometer in shunt to the working part of the slide wire, makes no appreciable difference to the current through it. Then move the slider contact E to E_1, to obtain the galvanometer's deflection D, whose current value it is required to know. Then a P.D. equivalent to the potentiometer scale reading AE_1 will be sending the current, I, through the resistance R + G, or $I = a\,\frac{AE_1}{R+G}$, where a is the the constant of the potentiometer scale, and the galvanometer constant $K = \frac{I}{D}$.

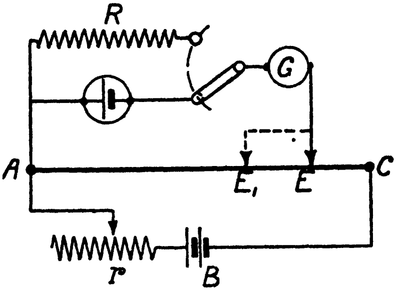


FIG. 161.—Galvanometer Calibration by Potentiometer.

As an example, suppose the potentiometer is adjusted so that there is a fall of 0·001 volt per scale division, and that the galvanometer to be calibrated has a resistance of 10,000 ohms, and the resistance connected in series with it across the working part of the slide wire is 5000 ohms.

Let the galvanometer deflection be 40 divisions when the tapping points on the slide wire are 20 divisions apart; then the P.D. applied to the galvanometer circuit is $20 \times \cdot 001 = \cdot 02$ volt, hence $I = \cdot 02/(10{,}000 + 5000) = 1/(7\cdot 5 \times 10^5)$, and

$K = 1/(40 \times 7{\cdot}5 \times 10^5) = 1/3 \times {\cdot}1/10^7$ or 1/30th micro-ampere per scale division.

A mean determination of K should be found from several values of D.

To calibrate a low-tension voltmeter by potentiometer (Fig. 162) we must make use of a volt-box, or series of resistance coils with tappings at 1/10th, 1/100th, or 1/1000th of the total value, which should be high, say 10,000 or 20,000 ohms.

The volt-box XYZ is connected in shunt to the voltmeter V and a suitable source of constant E.M.F. (*b*), as shown. Potential connections are then taken from that small fraction of the volt-box resistance across which there is a drop of about 1 volt, and this P.D. is then checked in the usual way against the E.M.F. of a standard cell. The checked P.D. is finally multiplied by the volt-box ratio to obtain the true voltage of the supply E.M.F. used for calibrating the voltmeter. Thus to check a voltmeter on 100 volts a secondary battery of 50 cells is necessary, and a volt-box with a ratio of sections 1 : 99. The checked P.D. across the unit coil must be multiplied by 100 to give the reading required for the voltmeter.

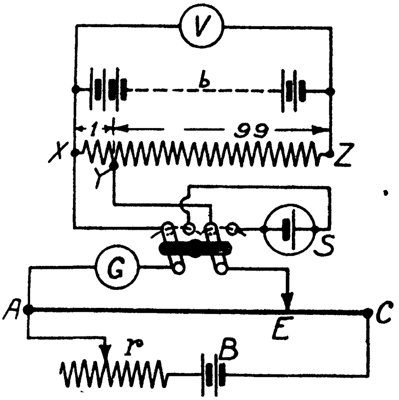


FIG. 162.—Voltmeter Calibration by Potentiometer.

In many commercial potentiometers the part of the wire over which the slider works is reduced to a minimum, in some cases to 1/100th or 1/150th of the full scale wire, the remaining part being split up into two sets of coils—one of coarse, the other of fine division—having intermediate connections to contacts fitted with regulating handles with which the necessary tapping points for balancing are found.

The slider wire should be made of some non-oxidisable metal, and should work if possible under glass in order to keep the contact free from dust, as the E.M.F. supplying the galvanometer current becomes less and less as balance is approached, and a dirty contact may interrupt the current altogether before a true balance is obtained. For careful work the sensitivity of the galvanometer should be such as to give a deflection of about 15 to 20 centimetres per micro-ampere, at a scale distance of one metre. The resistance of such an instrument would be about 500 ohms. A good potentiometer should measure directly as high as 1·5 volts, so as to cover the range of E.M.F. of all types of standard cell, and as low as ·00001 volt in order to make use of fairly low resistance standards for measuring heavy currents.

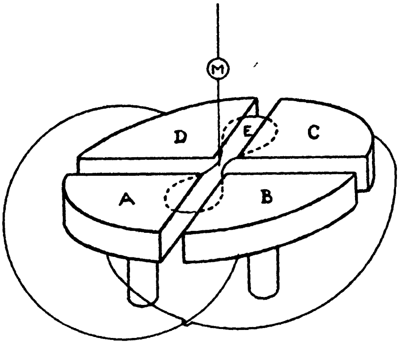


FIG. 163 (*a*).—The Quadrant Electrometer.

The Quadrant Electrometer.—To measure a static potential such as that due to a charge on a condenser, an instrument which absorbs a negligible amount of energy is required.

The most suitable form it can take, therefore, is that of a condenser of very small capacity, which employs the electrostatic forces of attraction and repulsion between those parts which are at different potentials, to create a movement which can be calibrated.

In the quadrant electrometer (Fig. 163 (*a*)) there are three essential parts:

(1) Two highly insulated brass quadrant boxes A and C, which are connected together and charged to the same potential;

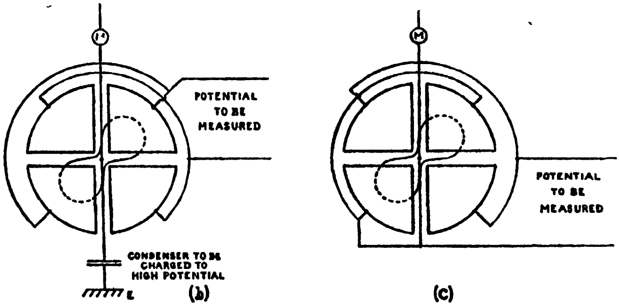
(2) Two other similar quadrant boxes B and D, also connected together, which are charged to some other potential; and

(3) A light aluminium moving vane E, which for certain tests is earthed, while for others it is charged to a very high potential, and which responds by deflection to the resultant electrostatic couple exerted by the quadrants. The movement is indicated on a scale by a spot of light reflected from the

mirror M, and is controlled by the torque on the vane suspension.

In the original Thomson electrometer the aluminium vane was charged to a high potential by means of a Leyden jar, the potential to be measured was applied to one pair of quadrants and the other pair was earthed (Fig. 163 (*b*)). Under such conditions the deflection of the vane is *directly* proportional to the potential to be measured.

The Dolezalek electrometer is of much lighter construction; it is more convenient to use as it does not employ a Leyden jar, and is a more sensitive instrument. The moving vane is of silvered paper, suspended by a quartz fibre which can be made conducting by a solution of calcium chloride, so that the vane may be charged by a battery to about 80 volts. It has a working capacity of about 50 cm., and it gives a deflection on a scale one metre distant of about 0·01 volt per centimetre.



FIGS. 163 (*b*) and (*c*).—Electrometer Connections for measuring Low and High Potentials.

To measure a high potential, one set of quadrants should be connected to the vane and to the source of high potential. The other pair of quadrants must be charged from a source of low potential (Fig. 163 (*c*)).

Then the deflection which results will be proportional to the *square* of the difference of potential established between the two pairs of quadrants.

This method of testing is also applicable to the measurement of alternating potentials.

Current and Potential Indicating Instruments.—Pointer indicating instruments which measure current directly by deflection over a calibrated scale, are called *ammeters.*

Pointer indicating instruments which measure directly the potential difference between two points in a circuit by deflection over a calibrated scale, are called *voltmeters.*

All ammeters are electromagnetic; voltmeters may be either electromagnetic or electrostatic.

The first essential quality of an ammeter is,—that its effective resistance must be so small, that, when the instrument is placed in series in the circuit, it shall have a negligible effect in reducing the current which it is required to measure; whilst a voltmeter must have so high a resistance—either contained in its coils, or added externally,—that it makes no appreciable difference to the potential drop between the two points where it is connected in shunt to the circuit.

Apart from this resistance factor, and the modifications in design which are necessitated by the different current-carrying capacities of the windings, there is no fundamental divergence either in the construction or in the theory of electromagnetic ammeters and voltmeters.

Some types of ammeters, for instance, which have a definite current limitation, are used with shunts for the measurement of heavy currents, and they then act as voltmeters, measuring the potential difference between the two ends of the shunt for various values of the main current.

A potential difference of this kind is always very small, and the instruments which measure it are therefore called *milli*-voltmeters, the term ammeter being used to describe the combination of milli-voltmeter with shunt.

"Hot-Wire" instruments, however, cannot be so described, as, when shunted, the measuring wire always carries an appreciable proportion of the total current.

The several types may be divided into three fundamental groups:

(1) Instruments which are suitable for Direct Current only—(*a*) the moving coil type.

(2) Instruments suitable for both Direct Current and Alternating Current—(*b*) the dynamometer; (*c*) soft iron; (*d*) thermal types.

(3) Instruments suitable for Alternating Current only—(*e*) the induction type, which it will be sufficient to simply mention here, as such instruments are more subject to frequency and temperature errors than are found in other A.C. types, and therefore they are not in very general use.

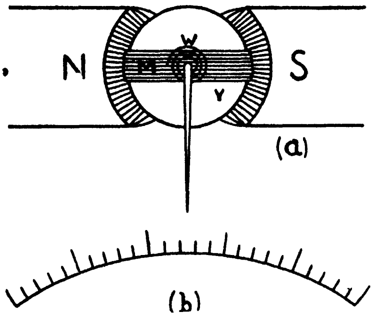


FIG. 164.—The Moving Coil Ammeter.

The Moving Coil Principle.—A pivoted coil, M (Fig. 164 (*a*)), carrying the current to be measured, is placed in the field of a permanent magnet NS, and its movement is controlled by a spiral spring W.

A soft iron yoke Y, placed inside the coil, reduces the air gap to the smallest practicable limits; maintains the permanence of the field; and causes it to be radial, and to have a constant intensity throughout the range of movement of the coil M.

The deflection obtained is due to the mechanical reaction between the variable current and the fixed magnetic field, and is therefore proportional to the first power of the current, so that the instrument measures the average of instantaneous values.

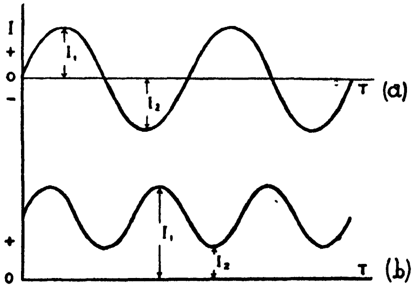


FIG. 165.—Alternating, and Variable Direct Current.

The average value of an alternating current (Fig. 165 (*a*)) is $(I_1 + I_2)/2 = 0$, so that the instrument is not suitable for measuring alternating currents.

The average value of a fluctuating direct current (Fig. 165 (*b*)) will be given by the mean height of the current ordinates, or by $(I_1 + I_2)/2$, which in this case is a measurable value.

The scale of such an instrument is equally divided, as shown in Fig. 164 (*b*).

The Dynamometer Principle.—The current to be measured, or—in the case of a voltmeter—the current resulting from the E.M.F. to be measured, passes through a pivoted coil M (Fig. 166 (*a*)), which is constrained by a spring and fitted with a pointer, and then through one or more fixed coils F, in series with M.

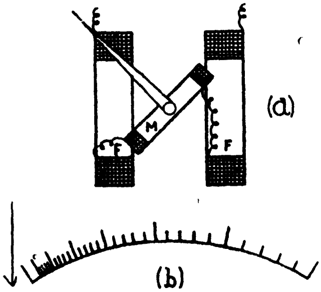


FIG. 166.—The Dynamometer Ammeter.

The movement of the pointer is caused by the mechanical reaction between the currents in the fixed and moving coils, and, as it is the same current which varies the magnetic fields of both coils, this movement is proportional to the second power of the current.

However, it is the first power of the current which we desire to know, so the scale is calibrated in proportion to the square root of the coil or pointer deflection.

If the current is fluctuating, or alternating, the deflection is proportional to the *mean square* value, and the scale reading is therefore proportional to the *square root of the mean square*, or R.M.S. value.

If Fig. 167 (*a*) represents an alternating current, the coil movement will be proportional to I^2 (Fig. 167 (*b*)), and as this is always positive, the instrument will be suitable for measuring alternating current. The scale is diverging, as shown in Fig. 166 (*b*).

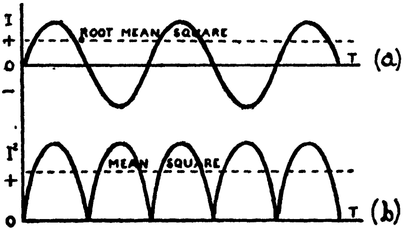
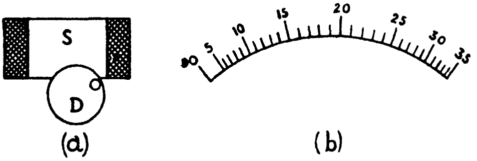


FIG. 167.—The Square, Mean Square, and Root-Mean-Square Values of Current.

Soft Iron Ammeters.—In the Everett-Edgecumbe model, a soft iron disc D (Fig. 168 (*a*)), on a spring-controlled pointer spindle, is drawn into a solenoid S, which carries the current to be measured.

If the disc is magnetically unsaturated, the movement will be proportional to the magnetic pull of the solenoid and the induction in the disc, and as both these quantities are proportional to the current in the solenoid, the deflection will be proportional to the square of the current. If the current is so large as to cause the disc to become saturated, then the movement will be proportional to the field of the solenoid only, and therefore to the first power of the current.



(a) (b)

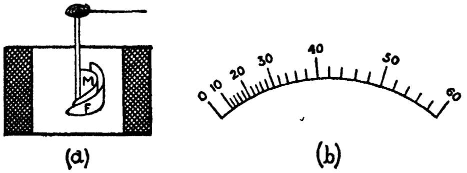
FIG. 168.—The Everett-Edgecumbe Soft-Iron Ammeter.

Then the scale — which is calibrated to read the first power of the current over its whole range—is likely therefore to be open at the middle and closed at both ends, as shown in Fig. 168 (*b*).

As the induction in the disc reverses with the current, the instrument is suitable for reading both on D.C. and A.C.

In the Weston model, the current to be measured flows through the winding of a solenoid (see Fig. 169), inside of which are two soft iron vanes. One of these vanes, M, is movable, being carried by the pivoted pointer spindle, while the other, F, is fixed.

The solenoid current magnetises them both to like polarity, so that they repel each other; and as the induction in both vanes is increased by the same current, the movement is proportional to the square of the current, and the reading given by the pointer to the R.M.S. value.



(a) (b)

FIG. 169.—The Weston Soft-Iron Vane Ammeter.

The vanes are shaped to give the best working scale, which has the general character of Fig. 169 (*b*).

Thermo-Ammeters.—A very common design is that due originally to Messrs. Hartmann and Braun.

The current to be measured, I, is passed through a fine platinum-silver wire of resistance R, which is stretched between two fixed points A and B (Fig. 170).

A fine phosphor-bronze wire is attached to the centre of AB at C, and to a fixed point D; also a silk fibre is attached to some point E in CD, and is then taken one turn round a pulley P carrying a pointer, to a spring F.

The current generates heat in the wire AB proportional to I^2R, which causes it to expand and to sag, with the result that the wire CD also sags, and the silk thread pulls the pulley round as the spring takes up the slack.

Fig. 170 also illustrates the manner in which the actual expansion is magnified.

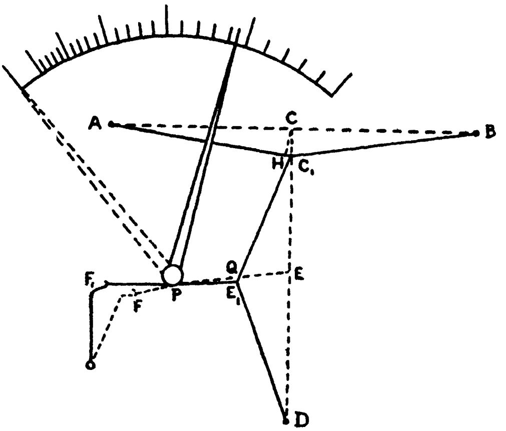


FIG. 170.—The Hartmann-Braun Hot-Wire Ammeter.

If the part of the wire AC when heated by a given current is increased in length by an amount HC_1, this will give the wire CD a movement CC_1, which in a similar manner will convey an increased movement to the silk thread, so that the amount taken up by the spring will be $PE - PE_1 = QE$.

The angle of deflection which results from this movement depends on the diameter of the pulley; and the length of the scale on the length of the pointer.

The scale is divergent, similar to Fig. 166 (*b*), and the reading gives the R.M.S. value of the current.

In order to multiply the current-carrying capacity of the expanding wire, it may be so connected to the terminal bars of the instrument as to provide several paths in parallel for the current.

Thus in Fig. 171 (*a*) the current enters the system at X and leaves at Y. The part AC of the expanding wire is in parallel with the part CB, and the total current capacity of the wire is thereby doubled.

In Fig. 171 (*b*) the wire AB is split up into six parallel paths for the current.

Ammeters which work on thermal principles are the only types used in practice to measure high-frequency currents.

Their accuracy depends (1) on the constancy of resistance of the expanding element at different frequencies; (2) on the distribution of current at different frequencies when the expanding part is sectionalised.

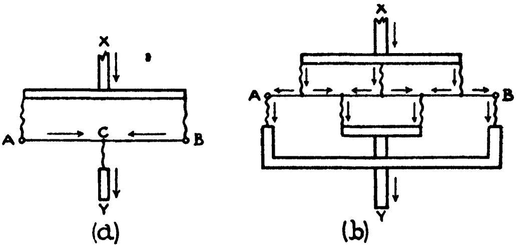


FIG. 171.—Methods of increasing the Current-carrying Capacity of Hot-Wire Ammeters.

Constancy of resistance with change of frequency can be obtained by using a measuring wire of high resistance and small diameter, or alternatively a very thin strip of high resistance as the expanding element.

In Fig. 171 (*b*), the resistance of the terminal bars X and Y may be negligible compared with that of the measuring wire, but the difference in inductance of the various paths to AB may be such as to create unequal distribution of the current at high frequency, which will introduce error in the instrument readings.

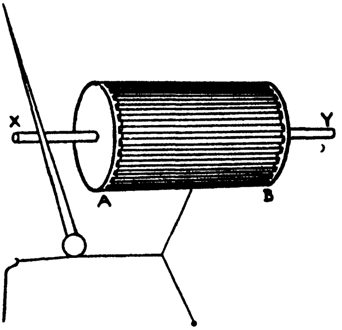


FIG. 172.—The Hartmann-Braun High-Frequency Ammeter.

A form of construction adopted by Hartmann and Braun, which aims at even current distribution, is illustrated in Fig. 172. The current to be measured passes through a drum consisting of a number of thin narrow platinum-silver strips of equal resistance, screwed on to the peripheries of two circular solid metal end-plates.

The expansion of one of these strips, AB, is measured in the manner already described. In this case the difficulty is to ensure that the strips have equal resistance.

The Duddell Thermo-Ammeter — which is suitable for measuring small high-frequency currents—is a moving coil instrument fitted with a thermo-couple and a non-inductive high-resistance heater wire.

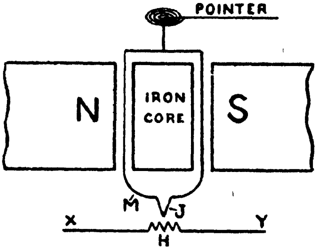


FIG. 173.—The Duddell Thermo-Ammeter.

The current to be measured is passed through the heater H (Fig. 173), which rises in temperature and warms the thermo-junction J. An E.M.F. proportional to the heat received, and therefore to I^2, is thereby generated in the junction, which causes a current to circulate through the moving coil M. This current reacts with the field of the permanent magnet, and the coil with its pointer is deflected.

Parallel wire ammeters are also used with thermo-junctions. In one form (Fig. 174 (*a*)) the junction J is attached to the centre of the middle wire, the resulting current being read off a low-resistance pointer galvanometer G. But as it is always better to make use of the whole heat production of the instrument in order to prevent errors due to unequal current distribution, the arrangement shown in Fig. 174 (*b*) is to be preferred. The wires are bridged with the two metals used in the thermo-junction—in this case copper and eureka—alternately, and in series, leaving two free ends of opposite metals to connect to the galvanometer.

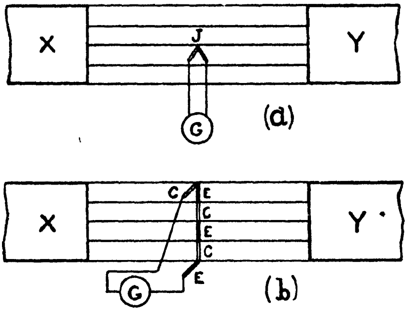


FIG. 174.—Parallel Wire Ammeters with Thermo-Junctions.

In the Marconi-Ewen ammeter for small currents (Fig. 175), two fine wires of platinum-iridium are stretched taut from two fixed points, A and B, to a pivoted bridge piece C, which carries a pointer P.

A hair spring attached to the bridge spindle is given a set, which is resisted by the torsion thereby applied to the two fine wires.

The current to be measured is passed through the wires and heats them so that they increase in length and offer less resistance to the twisting moment of the spring, with the result that the bridge pointer is deflected.

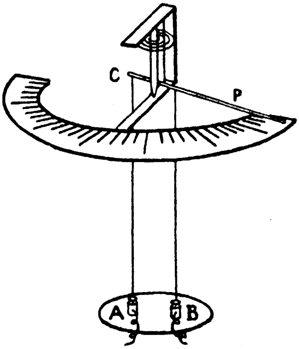


Fig. 175.—The Marconi-Ewen Ammeter for Small Currents.

The Marconi-Ewen ammeter for heavy currents (Fig. 176) employs a thin cylinder of resistance metal as the heating element H, which carries the whole current, and its longitudinal extension is measured by the increase in tension it conveys to two wires which are under the influence of a torsion impressed on them by a controlling spring. The wires are fitted in a somewhat similar manner to those in the smaller instrument, but they are only used for measuring purposes, not for carrying current. They are stretched taut between two lugs on the free end of the cylinder, and a collar on a spring-controlled spindle supported from the base of the instrument. Only the top part of this movement can be seen in the illustration.

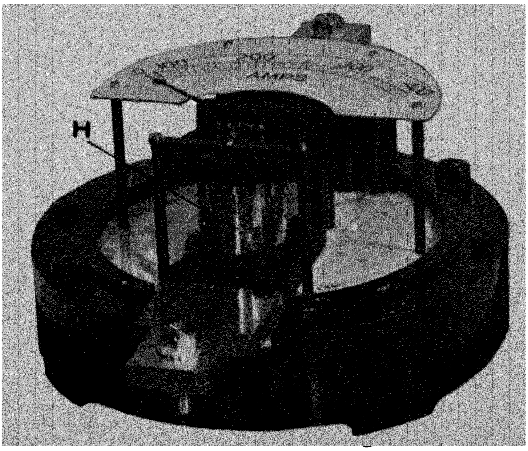


Fig. 176.—The Marconi-Ewen Ammeter for Large Currents.

The R.M.S. current is indicated, and the scale is diverging.

For the measurement of heavy high-frequency currents, however, it is much more convenient and quite as accurate to make use of a properly designed air-core transformer, with a low current thermal instrument connected to its secondary as indicator, as described by A. Campbell and D. W. Dye,[1] instead of an instrument which carries the whole current.

An illustration of a 4-amp. Marconi-Ewen ammeter connected to a 1 : 100 air-core transformer, so that at full scale deflection it indicates 400 amps., is shown in Fig. 177.

The straight cable primary may be part of the earth lead; in this case it is a section of 256/18 with hemp core, and the secondary is a ring winding on a wooden former in two sections, clamped round the primary.

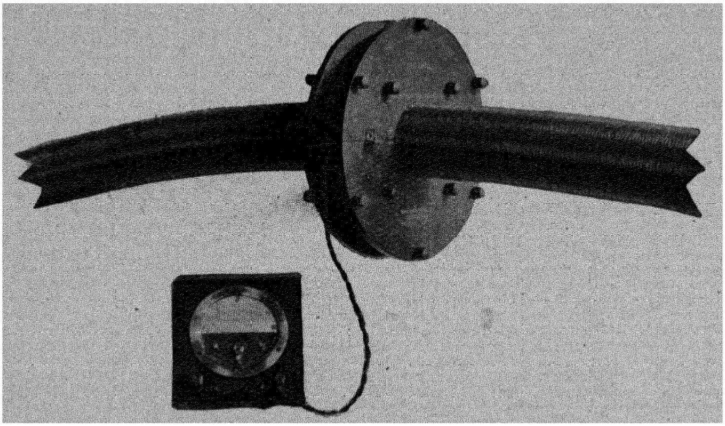


FIG. 177.—An Air-Core Current Transformer used with a Marconi-Ewen Ammeter.

The Electrostatic Voltmeter.—If two hollow quadrants, A and B (Fig. 178 (*a*)), are oppositely electrified by a potential difference V, and a vane, C, suspended so as to move inside them is electrically connected to one of them, A, then it will be repelled from A and attracted to the other quadrant B with a total force which over a short range varies as the square of the potential difference, or as V^2.

The moving vane may have either a gravity or spring control.

For measuring medium voltages, such as 100-500 volts, the number of fixed segments and moving vanes are multiplied, as shown in Fig. 178 (*b*).

[1] See *The Electrician*, March 19, 1915

Fig. 179 illustrates a Kelvin *volt-balance*, vertical type instrument, used for the measurement of potentials of the order of 10,000 volts. In this case the electrostatic force is balanced against gravity, and the range of the instrument can be altered by weighting the vane.

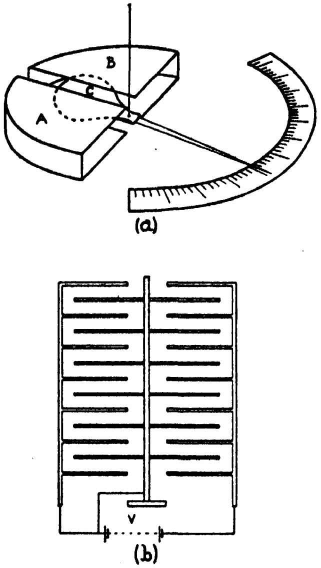


Fig. 178.—The Electrostatic Voltmeter.

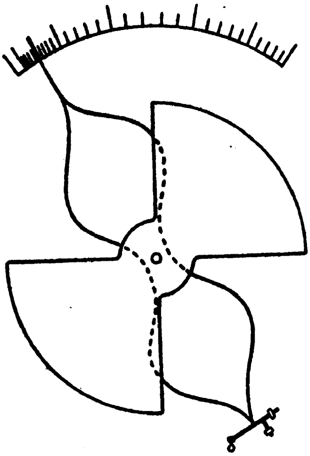


Fig. 179.—The Kelvin Volt-Balance.

Electrostatic voltmeters give R.M.S. readings, and their particular advantage is that they absorb no power.

CHAPTER VIII

THE MEASUREMENT OF RESISTANCE

Steady Current Resistance.—The "Ohm."—Large Current Sub-Standards.—The Wheatstone Bridge.—The Slide Wire Bridge.—The Plug Bridge.—The Post Office Pattern.—Method of using the Bridge.—Portable Bridge with Paul Galvanometer.—The Measurement of very Small Resistances.—The Potentiometer Method.—The "Ducter Potential Ohmmeter."—The Ohmmeter.—Resistances of 1 *Megohm and above.—Insulation Resistances.—The "Guard Wire."—The "Megger."—Insulation and Dielectric Resistances of Millions of Megohms.—The Use of a Ballistic Galvanometer,—of an Electrometer.*

Steady Current Resistance.—The "ohm," the unit of resistance, is the true electrical resistance at 0° C. of a column of mercury 106·3 cm. long and 1 square millimetre in cross-section, measured with an unvarying direct current.

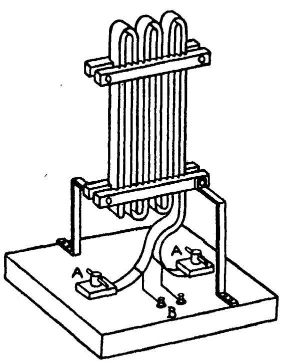


FIG. 180.—A Resistance Standard of 0·1 Ohm, to carry 15 Amperes.

In the commercial laboratory this is represented (1) by large current sub-standards of strip or wire having values of 1 ohm, ·1 ohm, ·01 ohm, etc., made of a metal which has a very low temperature coefficient,[1] such as manganin, platinum-silver, or platinoid, and constructed in a non-inductive manner. Fig. 180 shows a ·1 ohm standard, suitable for carrying 15 amperes. The current enters and leaves it by the "current terminals" A, and its specified resistance is given between the "potential terminals" B.

---

[1] The percentage change of resistance with change of temperature per degree centigrade.

(2) By the Wheatstone Bridge, an instrument generally composed of a large number of such sub-standards, but suitable only for very small currents, assembled in one box, and so connected that they can be used to measure unknown resistances within a wide range above and below their own values.

The Wheatstone Bridge.—The principle on which this instrument works is as follows:

ADC and AEC (Fig. 181) are two branch circuits fed with current from a battery B. The fall of potential will be the same down each of them, therefore if we connect a current detector G to any point E, in AEC, we can find a corresponding point D, in ADC, having the same potential as E, at which no current will flow through G. In this condition the "Bridge" is said to be "balanced." If P, Q, R, S are the respective resistances of the arms of the bridge, the fall of potential along P will then be the same as the fall along R, and the potential fall along Q must equal the fall along S. Also, as no current flows from D to E, the same current will flow through Q as through P, and the current in R will be the same as in S.

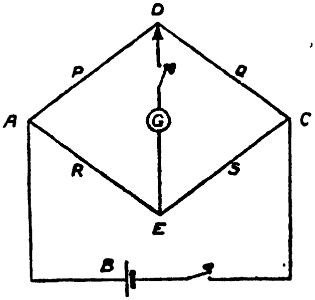


FIG. 181.—The Working Principle of the Wheatstone Bridge.

Let V_P, V_Q, V_R, V_S be the respective falls in potential; and I_P, I_Q, I_R, I_S the respective currents; then $V_P = V_R$, and $V_Q = V_S$; also $I_P = I_Q$, and $I_R = I_S$.

But by Ohm's Law

$$\frac{V_P}{I_P} = P, \ \frac{V_Q}{I_Q} = Q, \ \frac{V_R}{I_R} = R, \ \frac{V_S}{I_S} = S.$$

Then

$$\frac{P}{Q} = \frac{R}{S}; \text{ or, } R = S\frac{P}{Q}.$$

In the practical case (Fig. 182) R would be the unknown resistance, S the standard of comparison, P and Q a slide wire mounted on, or in front of, a metre scale, and tapped by a travelling connection at the point D. The ratio $\frac{P}{Q}$ will be given by the ratio of the two lengths into which the slide wire is divided at the point D. It is usual to have a number of standards at S, either one of which can be plugged in circuit, that one being used which brings the tapping point D nearest to the centre of the slide wire, as there is then least error in the measurement.

But the slide-wire form of Wheatstone Bridge can only measure resistances within a limited range. It is therefore only used as supplementary to what is known as a "Plug" or "Coil" Bridge, an instrument constructed to measure resistance values within a very wide range, say between ·001 and 10 megohms, or ·0001 and 1 megohm. In this instrument the connection at D is fixed; the two ratio arms P and Q, and the measuring arm S, are made up of resistance bobbins which can be plugged either in or out of circuit, according to the method of construction adopted. Thus in the "Series" or Post Office Bridge (Fig. 183) the plugs are used to short-circuit sections of the total resistance, whereas in the "Dial" and "Bar" patterns (Fig. 184 (*a*) and (*b*)) plugs are employed to tap off from sections of the resistance. The last method reduces the liability to error from faulty plug contacts.

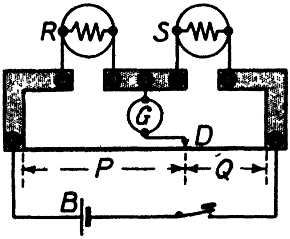


FIG. 182.—The Slide-Wire Wheatstone Bridge.

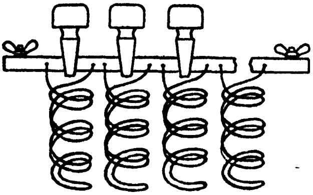
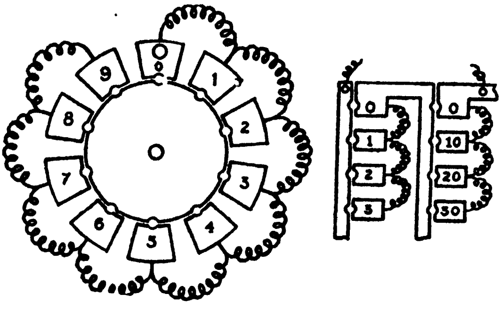


FIG. 183.—Post Office Plug-Bridge; Method of connecting the Coils.

A diagram of a commercial Post Office Bridge is shown in Fig. 185.

The ratio arms each have usually a series of four coils, 1 ohm, 10 ohms, 100 ohms, and 1000 ohms—three only are shown in the figure—and the measuring arm a much larger series which will allow any resistance, say from 1 ohm to 10,000 ohms, in unit steps, to be inserted in circuit. The terminals BB are connected to the battery, GG to the galvanometer, and RR to the unknown resistance. This having been done, a measurement is made as follows :



(*a*) (*b*)

FIG. 184.—"Dial" and "Bar" pattern Coil Connections.

First insert resistances in the two ratio arms which give an equality ratio, by removing, for instance, the two 10-ohm plugs. Then, by removing plugs from the measuring arm, try to balance the unknown resistance so that on depressing first the battery key KB, and then the galvanometer key KG, no deflection results.

The value of the resistance under test is then given, as before, by the ratio of the two resistances in the ratio arms multiplied by the resistance in the measuring arm, or by $R = S\frac{P}{Q}$.

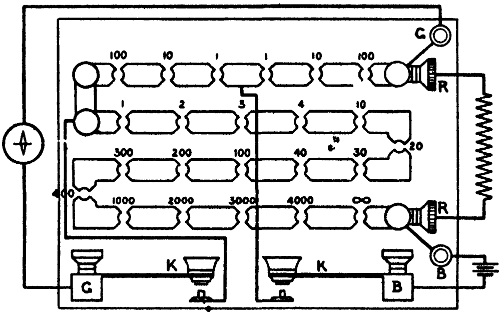
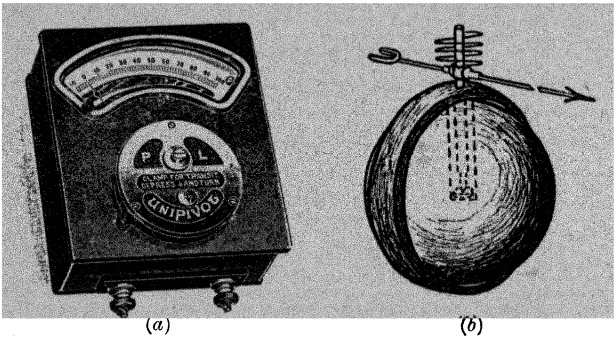


FIG. 185.—Diagram of Post Office Bridge Circuit.

The closest approximation is obtained by making use of the whole range of the measuring arm, units, tens, hundreds, and thousands. Thus suppose the resistance found, using an equality ratio, is 21 ohms, then only the units and tens coils in the measuring arm will have been used. By altering now the ratio arms to 10 and 1000 ohms respectively, th hundreds and thousands coils in the measuring arm will also come into use, and the resistance under test can then be measured to the second place of decimals. Resistances greater than the maximum value in the measuring arm can of course only be measured by using a high ratio, and resistances less than the minimum value by using a ratio less than unity.

The galvanometer used with the Wheatstone Bridge is simply a current indicator. In the workshop, where approximate measurements are all that is required, a robust pointer instrument would be used. For very rough work a " linesman's detector "—in which a magnetic needle is free to move on its axis in a coil of wire carrying the current—may do. Its resistance would be about 100 ohms, and sensitivity—two scale divisions per milliampere. For better work an instrument such as is shown in Fig. 186 (*a*) would be employed. The current-carrying coil in this case is pivoted, and moves in a strong magnetic field. Its resistance would also be of the order of 50 ohms, or 100 ohms, and its sensitivity about half a scale division per microampere. The single-pivot movement adopted by R. W. Paul which is here illustrated (Fig. 186 (*b*)) has the advantage that it has a minimum of pivot friction, is free from out-of-level error, and, considering the sensitivity obtained, it is very robust and portable.



(*a*) (*b*)

FIG. 186.—Single Pivot Galvanometer of R. W. Paul, showing Movement.

In the test room accuracy is essential, and the bridge must be provided with a fairly sensitive galvanometer, but there is no need for it to be highly sensitive. A quick-acting, strongly - damped reflecting galvanometer of the

D'Arsonval type—moving coil and fixed magnet—is most commonly used. Fig. 151 (*a*) shows the details of such an instrument. Its sensitivity should be such that it gives a deflection on a scale placed at a metre distance of 25 mm. to 100 mm. per microampere, according to the number of turns in its coil and therefore to its resistance, which may be anything from 200 ohms to 500 ohms.

The battery must be well insulated, and is required to give an occasional momentary current, which may reach perhaps ·25 ampere, but in general testing is more often a few milliamperes. Generally, one small, but good, dry cell is sufficient.

The "Fall of Potential" Method.—Very small resistances, say 0·1 ohm and less, can often be measured better by a "fall of potential" method than by a "bridge" method, as the error introduced by the resistance of contacts can then be reduced to a minimum. Thus, suppose it is required to measure the resistance of a dynamo armature, or a short length of cable. Select a known standard resistance S, of about the supposed value of the unknown R. Join the two in series with a variable resistance *r*, and a battery of several cells B (see Fig. 187).

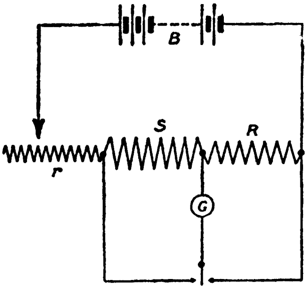


Fig. 187.—Fall of Potential Method of measuring Small Resistances.

Then use a high-resistance galvanometer, or one with a series resistance of such an order—say 2000 ohms—that when connected across either of the low resistances it makes no apparent difference to the fall of potential down it. This galvanometer, unlike the instrument used on the Wheatstone Bridge circuit, is required to be a current measurer, not simply a detector, and therefore should have good zero keeping qualities. Then if the deflection D_S represents the value of the current through the galvanometer when it is connected across S, due to the fall of potential down S, and D_R the resulting galvanometer current which is the measure of the potential fall down R, then $\frac{D_R}{R} = \frac{D_S}{S}$, as the same main current passes through both resistances, and $R = S\frac{D_R}{D_S}$. If the deflection is not absolutely proportional to the galvanometer current, then D_R and D_S should be replaced in the foregoing expression by their current equivalents as found by calibration. It is not desirable that either of the galvanometer deflections should be large, hence the use of the adjustable resistance r. The connections should all be soldered, or made in mercury cups, a quick throw-over method of changing G from R to S should be used, and several sets of readings should be taken to ensure that no error occurs through slight variations in the main current.

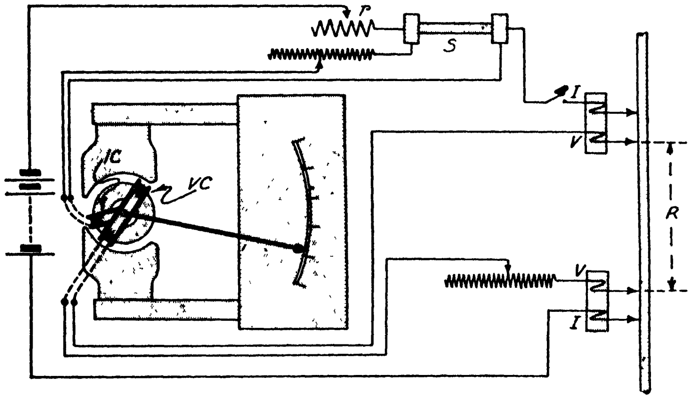


Fig. 188.—The "Ducter Potential Ohmmeter."

If great accuracy is not required, a suitable voltmeter may be used in place of the galvanometer at G.

The "Ducter Potential Ohmmeter."—A portable instrument for measuring very low resistances—from 0 to 500 microhms on one scale, and up to 5 ohms by the use of a multiple switch—known as the "Ducter Potential Ohmmeter"[1] or "Ducter," is often found useful for commercial work, particularly as it is direct reading. Fig. 188 is a simplified diagram of its internal connections, showing also the method of connecting to the test piece.

The place of the galvanometer is taken by an "ohmmeter," an instrument whose moving part consists of a current coil and a potential coil fixed on one axle, with their magnetic axes at a definite angle to each other, moving in the field of a permanent magnet. The reactions between the current in each coil and the field, produce two torques on the axle, but these torques are in opposition, so that the resulting deflection depends on the ratio of potential drop to current, and thus to resistance, as $\frac{V}{I} = R$.

---

[1] Made by Evershed & Vignoles, Ltd.

The current coil, IC, is connected across the shunt S in the main circuit, and the current which flows through it is proportional to the main current. The potential coil, VC, is connected across the test piece R, and the current which flows through it is proportional to the potential fall down R.

Two insulating handles, each fitted with a pair of spring-contact test-spikes I and V, make a current and potential connection to the unknown resistance R, the handles being applied so that the potential spikes come between the current spikes on the test piece. A secondary battery giving 2 volts is required for the measurement of resistances at the bottom range of the instrument, and giving 8 volts for resistances above 1 ohm.

Measurement by Direct Galvanometer Deflection.—The measurement of resistances of 1 megohm and upwards can be obtained with greater accuracy by a direct galvanometer deflection method than on a Wheatstone Bridge. The galvanometer G (Fig. 189) must be a highly sensitive mirror instrument, having a millimetre scale placed at a distance of 2 metres. Its resistance should be of the order of 5000 ohms to 10,000 ohms. It must keep its zero, and its constant G—the figure by which the scale deflection D must be multiplied to give amperes—should be the same over the whole working range of the scale. The battery B should have an E.M.F. of about 100 or 200 volts. The complete circuit—battery, galvanometer, key, leads—requires to be well insulated from earth.

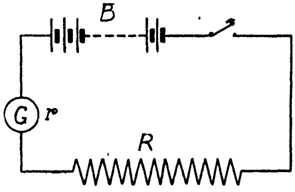


FIG. 189.—Resistance Measurement by Direct Galvanometer Deflection.

The current in the circuit, I, which results from the battery voltage E, and the total resistance of the circuit which comprises R the unknown, r the galvanometer resistance—and the resistance of the leads and battery which is negligible compared with the other values—is given by

$$I_{\text{amp.}} = G \times D = \frac{E_{\text{volts}}}{R + r},$$

and

$$R_{\text{ohms}} = \frac{E}{G \times D} - r.$$

The galvanometer must first be calibrated to determine G, either by sending a known current through it, measured by some other instrument of precision, and noting D, or else by potentiometer in the manner already described. Also the E.M.F. of the battery must be accurately determined—if dry cells, by an electrostatic voltmeter; if accumulators, by any efficient type of voltmeter; or, failing a voltmeter, by potentiometer.

Insulation Resistances.—Conductor resistances above 1 megohm are seldom met with, but insulator resistances—due to which the current creeps over or through the material—are of this order and upwards.

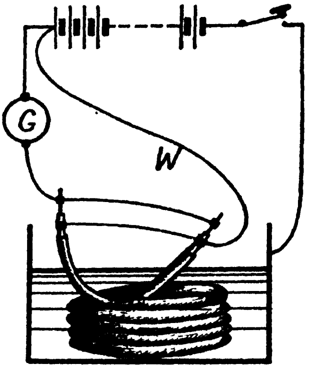


FIG. 190.—The Use of a Guard Wire for Insulation Tests.

It is usual to provide a "guard wire" whenever possible on insulation tests, which short-circuits the galvanometer to currents creeping *along the surface* of the material but leaves it free to measure the currents passing through it.

Thus, if, in place of R in the direct deflectional test above, a cable is inserted as in Fig. 190, whose insulation resistance it is required to measure, the two bared ends of the cable—which is placed in a metal tank filled with water—are connected to one terminal of the galvanometer, the other terminal and the tank are connected to the battery, and the guard wire W is wrapped round the rubber or gutta-percha exposed by the removal of the braiding, and connected to the galvo side of the battery. Then any leakage along the surface on reaching the guard wire is carried direct to the battery without passing through the galvanometer.

The "Megger"[1] is a portable instrument in very general use for measuring insulation resistances. It consists of a moving coil "ohmmeter," somewhat similar in construction to the ohmmeter fitted to the ducter, connected through the necessary resistances to the apparatus under test, and a hand-driven high-tension magneto-generator which provides the testing current.

The principle of the circuit is shown in Fig. 191. All tests are made between the "Line" circuit, connected to terminal marked L, and "Earth," connected to terminal marked E. A guard plate fitting protects the ohmmeter from leakage currents in the instrument, which plate should be connected to the guard wire used in cable tests as already described. The handle spindle of the generator is fitted with a free-wheel attachment to the gearing, which allows the machine to be driven only one way, and prevents any damage resulting due to the sudden stoppage of the handle. A constant voltage is obtained by the use of a centrifugal friction clutch between the gearing and armature, which uncouples the armature when the driving handle is turned above the critical speed. It is claimed that the E.M.F. does not vary more than 1 part in 1000 when running under such conditions.

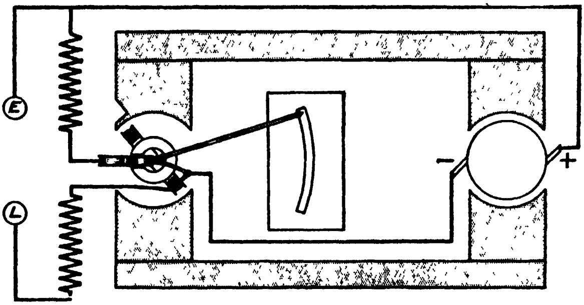


FIG. 191.—The "Megger" Connections.

---

[1] Made by Evershed & Vignoles. Ltd.

The lowest range instrument measures from 0 to 10 megohms at a constant pressure of 100 volts, and the highest range from 15 to 5000 megohms at a constant pressure of 1000 volts. 2000-volt generators are also now coming into use.

The "Loss of Charge" Method.—Insulation and dielectric resistances of millions of megohms are measured by a loss of charge method. The two test plates on the material are connected to a charged condenser C (Fig. 192), and the rate of fall of the charge due to leakage across or through the material is noted. Then if the galvanometer deflection D_0, obtained by taking the discharge immediately after the charge, falls to D_1, and if there is a time t seconds interval between charge and discharge, it can be shown that—

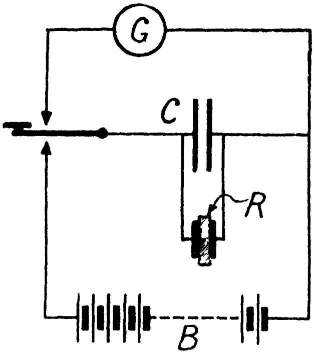


FIG. 192.—Insulation Resistance by "Loss of Charge" Method.

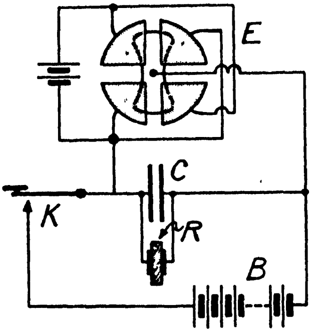


FIG. 193.—"Loss of Charge" Method, using an Electrometer.

$$R = \frac{\cdot 4343t}{C\left(\log_{10}\frac{D_0}{D_1}\right)}$$

and if T is the time interval in seconds for the condenser to lose half its charge, then $R = \frac{10T}{7C}$ nearly.[1]

Here R and C are in ohms and farads, or megohms and microfarads.

A *ballistic* galvanometer must be used, that is one with very small damping; it receives the full effect of the charge before it has completed its first swing, and the amplitude of this swing when suitably corrected for damping is the measure of the charge.

---

[1] See J. A. Fleming's *Handbook for the Elec. Lab. and Testing Room*, vol. i. p. 298.

Better results are obtained if an electrometer of small capacity and very high insulation is used instead of a galvanometer (Fig. 193). It need not be very sensitive, as the battery voltage can be made comparatively high, say 100 volts or more. The rate of fall of potential of the charged condenser can then be observed directly, and the electrometer may be left in circuit the whole time, but a correction must be introduced for the leakage resistance through the condenser and electrometer. This should be determined by the same method before the insulating material under test is joined in circuit. It must be subtracted from the total insulation resistance found when the insulator is in circuit, making use of the formula for resistances in parallel for this purpose.

CHAPTER IX

THE MEASUREMENT OF CAPACITY

The "Farad." — The Electrostatic Unit.—Specific Inductive Capacity.—Capacity by Direct Charge. — The Fleming-Clinton Commutator. — Circuit Connections. — The Capacity Bridge. — The Calibration of Marconi Glass Condenser Tubes. — Residual Charge. — Alternating-Current Measurement of Capacity. — The High-Frequency Resonance Method for Small Capacities.—The Effective Capacity of an Aerial.

The Measurement of Capacity.—The international electromagnetic unit of capacity, the "farad," is the capacity of a condenser which has its potential raised from zero to 1 volt by a charge of one coulomb (one ampere for one second). Imagine a sheet of ordinary window glass $\frac{1}{8}''$ thick and 20 square miles in area, covered on both sides with tinfoil. The condenser so formed would have a capacity of about 1 farad.

Obviously we require a smaller unit in practice, and the working unit has therefore been made one millionth of a farad, or the "microfarad." But the microfarad also becomes cumbersome to use when dealing with very small condensers, so that the capacity in free space of a sphere having a radius of 1 centimetre, the electrostatic unit, 9×10^5 of which are equivalent to 1 microfarad, then becomes a more suitable standard.

The present tendency is to adopt the "micro-microfarad" in place of the "centimetre"—$1 \cdot \dot{1}$ m.mfd. being equal to 1 cm.—in order that confusion may be avoided by providing for the measurement of the complete range of capacities in electromagnetic units.

The Specific Inductive Capacity of a material is the ratio of the capacity of a condenser which employs this material to completely fill the dielectric space between its conducting plates, to the capacity found when the material is replaced by air at atmospheric pressure.

A number of such values are tabulated below:

Substance.	Sp. Ind. Capacity.
Ebonite	2·0–3·15
Glass	3·0–9·0
India-rubber	2·1–2·9
Mica	8·0
Paper	2·0–2·8
Paraffin Wax	2·3
Porcelain	4·4–6·8
Quartz	4·5
Vaseline	2·2
Paraffin Oil	2·2–2·6

The specific inductive capacity of all gases at atmospheric pressure does not differ much from unity, but a proportional increase takes place with increase of pressure. Air at 100 atmospheres has a specific inductive capacity of 1·05.

Capacity by Direct Charge.—To compare an unknown condenser C_x against a standard C_s (Fig. 194), first charge the standard for a given time, say 30 seconds, then discharge it by instantaneous throw-over to a ballistic galvanometer G, and note the deflection D_s. Then change over to the condenser of unknown capacity C_x, charge for the same time, discharge as before, and note the galvanometer deflection D_x. Then the ratio of the two charges will be the same as the ratio of the two deflections. If V is the battery voltage,

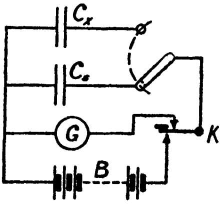


Fig. 194.—Capacity by Direct Charge.

$$VC_s : VC_x : : D_s : D_x$$

and

$$C_x = C_s \frac{D_x}{D_s}.$$

For example, a ballistic galvanometer having a resistance of 10,000 ohms, a time of swing 4·5 seconds, and sensitivity 6 cm. per microampere at 1 metre scale distance, when used with a 100-volt battery will give a 2-cm. deflection for a capacity of ·002 mfd., and 50 cm. for a capacity of ·05 mfd.

The direct discharge of a condenser through a ballistic galvanometer can be used to measure its absolute capacity if the steady current required to give the same deflection is known, but the method of test is not sufficiently simple to describe here.

The Capacity Commutator.—The absolute measure of very small capacities can conveniently be obtained by using the "Fleming-Clinton Commutator," a device for first charging, then insulating, and finally discharging a condenser through a galvanometer in a regular manner many times per second, so that the galvanometer gives a constant deflection.

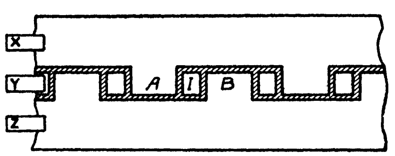


FIG. 195.—The Fleming-Clinton Commutator; the Surface laid out flat.

Then if I = current in microamperes corresponding to scale deflection D,
V = charging E.M.F. of battery,
n = number of commutations per second,
C = capacity of condenser under test in microfarads,

$$C = \frac{I}{n \times V}.$$

The surface of the commutator laid out flat is shown in Fig. 195, and its section in Fig. 196.

Three interleaving phosphor bronze discs A, B, and I, well insulated from each other and from a common shaft, form a drum which is fitted with three brushes and driven through an insulating flexible coupling by a $\frac{1}{4}$-h.p. motor, running at about 2000 r.p.m. Brush X connects to the galvanometer, brush Y to the condenser, and brush Z to the battery. As the commutator revolves, Y and Z come on the same disc and the condenser receives a charge, a little later each brush bears on a separate disc—the condenser is insulated from both battery and galvanometer; still further revolution causes Y to bear on the same disc as X, and the condenser discharges through the galvanometer.

The commutator completes its cycle of changes four times per revolution, and by means of reducing gear on the shaft rings a bell every 100 revolutions.

If T is the time in seconds required for the bell to ring 10 times, $n = \frac{4000}{T}$.

The circuit connections terminating at the commutator brushes are shown in Fig. 197; *rr* are protective resistances, each of 100,000 ohms; P and Q are long arm switches. The battery and every part of the circuit must be well insulated from earth.

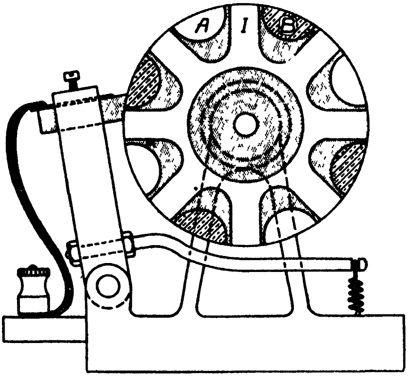


Fig. 196.—The Fleming-Clinton Commutator; Sectional View.

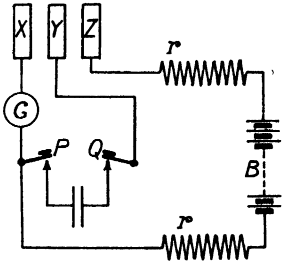


Fig. 197.—The Fleming-Clinton Commutator; Circuit Connections.

The galvanometer is first calibrated in microamperes per scale division, then $\frac{I}{D} = G$, the galvanometer constant.

The commutator being run up to speed, the following galvanometer deflections are noted.

(1) With switches P and Q open, the deflection due to the capacity of the whole circuit, exclusive of the condenser C, $= D_1$.

(2) With switch P closed and Q open, the condenser being short-circuited but connected to the switches, the deflection due to the circuit capacity plus capacity to earth of both sides of the condenser $= D_2$.

(3) With switches P and Q closed and the condenser in circuit, the deflection due to the total capacity of the circuit and the condenser, plus the capacity to earth, $= D_3$.

Then
$$C = \frac{\left\{D_3 - \frac{(D_1 + D_2)}{2}\right\} \times G}{nV}$$
$$= \frac{T\left\{D_3 - \frac{(D_1 + D_2)}{2}\right\} \times G}{4000V}.$$

With an aperiodic galvanometer of 500 ohms resistance, having a sensitivity at 1-metre scale distance of 7 centimetres per microampere, the range of test, using a 50-centimetres scale and suitable variation of commutator speed and battery voltage, will be from 0·00004 mfd. (36 cm.) to 0·002 mfd. (1800 cm.). The range of commutator motor speed must then be from 2600 r.p.m. to 900 r.p.m., and the range of battery voltage from 100 volts to 50 volts.

The method is not suitable for measuring the capacity of leaky condensers, as the charge will fall during the interval between breaking the condenser connection to the battery on the commutator and again making it to the galvanometer; nor for condensers of such a size that the speed of the commutator prevents them getting fully charged before they are disconnected from the battery.

The Capacity Bridge.—A convenient circuit for comparing an unknown capacity against a standard by a method of balance, generally known as a Capacity Bridge, is shown in Fig. 198.

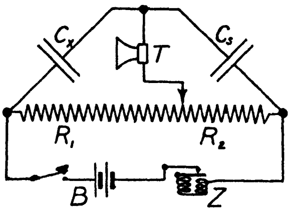


FIG. 198.—The Capacity Bridge.

The unknown condenser C_x is joined in series with a standard condenser C_s, across a two-cell battery B, which delivers an intermittent charging current due to the introduction of a high-note buzzer Z. The condensers are shunted by a resistance R_1R_2. As the same charging current flows through the two condensers, the P.D. maintained by the battery will be divided between them in the inverse proportion to their capacities. If R_1R_2 is a slide wire on a metre scale, and we make contact somewhere along its length, the P.D. down the sections into which it will be thus divided will be directly proportional to their resistances, and therefore to their lengths. A telephone, T, is joined at one end of the common connection of the two condensers, and at the other to a travelling contact on the slide wire. This contact is moved until a point is found at which no buzz is heard in the telephones. The bridge so formed will then be in balance, the point of contact on the slide wire being at the same potential as the common connection of the condensers. Then

$$\frac{C_x}{C_s} = \frac{R_2}{R_1};$$

and $$C_x = C_s \times \frac{R_2}{R_1}.$$

If the best adjustment on the slide wire does not lead to complete silence in the telephones, but only to a minimum of sound with a rise on either side, the want of balance is either due to imperfect insulation or to pronounced dielectric absorption in the condenser branches. A continuous fall in strength of telephone buzz all along the wire to the end, suggests that the point of balance is not in the exposed part of the slide wire but in the extension coil enclosed in the instrument to make the scale more open at its useful portion, and that a more suitable standard condenser should be used. With two standard condensers ·004 mfd. and ·08 mfd., and a metre slide wire of No. 28 Eureka, having a resistance of 4·18 ohms, with an extension coil of ·85 ohm at each end, a range in capacity measurement from ·0007 mfd. to ·5 mfd. can be obtained, and a further extension to the slide wire of 20 ohms by means of a switch will carry the useful range up to 2 mfds.

The Calibration of Glass Condenser Tubes.—The Marconi condenser tubes for ¼-kw. ship sets provide a good example of the use of the capacity bridge in manufacture. The capacity of these condensers must be within 2½ per cent above or below 600 cm., the height of foil to allow for variation in thickness and quality of the glass being within 1″ and 4″ from the top.

The raw tube, after being well cleaned and dried, is inserted in a glass container partly filled with mercury, in the calibrating stand shown in Fig. 199. As the tube tends to float, it is forced down into the mercury by means of a wooden slide which works in slots in the supporting frame, and can be clamped tight in any position in the slots. This operation causes the mercury to rise on the outside surface, thus forming an outer conducting coating. The inner conducting coating required to complete the condenser is formed by mercury which is poured into the tube, and elevated to the same level as the mercury outside by displacing it with an ebonite plunger rod, which also can be clamped in any position within the testing limits. A metallic connection passes down the centre of the plunger rod, and a connecting wire dips into the mercury surrounding the tube. The capacity of the tube is then measured on the bridge with different settings of the ebonite plunger rod and wooden slide, thus testing it with the glass surface covered with a conducting coating up to different levels, care being taken to keep the level inside and out the same.

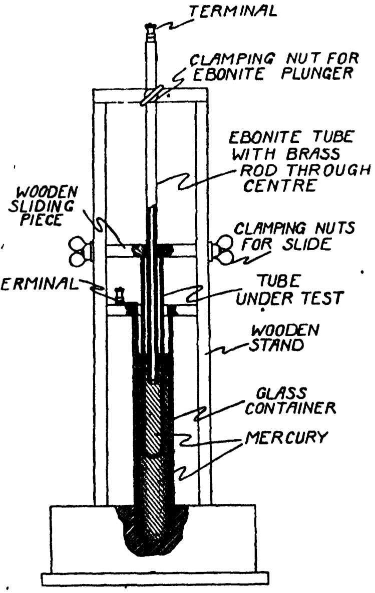


Fig. 199.—Apparatus used for the Preliminary Calibration before Plating of Marconi Tube Condensers.

When the correct height for the required capacity has been found, a gummed label printed with the capacity in centimetres is fixed on the outside of the tube with its lower edge at the mercury level. By means of a change-over switch the tube condenser with its mercury coatings is then connected to the high-frequency high-tension sparking circuit, on which it is tested for dielectric strength. On passing this test the mercury is emptied, the tube is cleaned, and it is sent to be copper-plated. The inside surface of the tube is varnished, bronze dust is blown on to the varnish, and the tube is then ready for the plating bath.

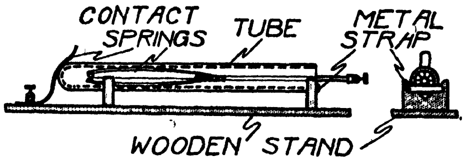


FIG. 200.—Stand used for Check Calibration of Plated Tube Condensers.

When the inner coating has reached the required thickness, the tube is withdrawn from the bath, and it is then prepared in a similar manner to receive a copper deposit on its outer surface. This plating process completed, it is cleaned, dried, varnished, baked, and then checked for capacity on the bridge to see that it comes within the $2\frac{1}{2}$ per cent limit, using the stand shown in Fig. 200 as a support.

Residual Charge.—All dielectrics, other than the stable gases, possess to a more or less degree the qualities of "soakage," or "absorption," and "residual charge"; that is, it takes time to charge them fully, and to discharge them completely.

The specific inductive capacity is not then a fixed quantity for any dielectric, but depends to a certain extent on the conditions under which the dielectric is used, on the frequency of the charge and discharge, also on the maximum voltage applied to the condenser, and on the energy density at which it is worked. If it is possible, therefore, to measure the capacity of a condenser under its actual working conditions, so much the better, particularly in the case of condensers used in power circuits for which the factor of safety—the ratio of breakdown load to working load—is not very high.

Alternating Current Measurement of Capacity.—In an alternating current circuit of sinoidal wave-form, *in which the conditions for resonance do not exist,*

$$I_{\text{r.m.s.}} = V_{\text{r.m.s.}} \Big/ \frac{1}{2\pi n C_{\text{farads}}}$$

or

$$C_{\text{microfarads}} = \frac{I_{\text{r.m.s.}} \times 10^6}{2\pi n V_{\text{r.m.s.}}},$$

where I is the charging current, V the potential difference measured across the terminals of the condenser by an electrostatic voltmeter or volt balance, and n is the frequency of the supply, the ohmic resistance R in the condenser being negligible. The above equation will give too high a value for the capacity if the voltage wave-form is not sinoidal; but given the wave-form, a suitable factor can be found to use in place of 2π to make the formula correct.

The Method of Resonance on High Frequency.—For small condensers a high-frequency resonance method is often found useful. A wave-meter is required which has a circuit so arranged that the condenser under test can be connected either in series or in parallel with its own condenser (see p. 296 and Fig. 278). Either the condenser scale must be calibrated in capacity C as well as wave-length λ, or the inductance L of the wave-meter circuit must be known.

Finally, a high-frequency current must be provided in a neighbouring circuit which gives a wave-length reading high up on the scale of the wave-meter condenser.

Then for capacities less than the maximum of the wave-meter condenser, tune up the wave-meter to the oscillating circuit, first without, and then with, the condenser of unknown capacity in parallel with its own condenser. The difference in the readings of the wave-meter condenser, if it is calibrated in capacity, will give the value of the unknown.

If λ and L are known, but C is not known, the two values of the wave-meter condenser can be obtained from the formula

$$\lambda = 1885\sqrt{LC},$$

whence

$$C = \frac{1}{L} \times \left(\frac{\lambda}{1885}\right)^2,$$

where C = capacity in microfarads.
L = inductance in microhenrys.
λ = wave-length in metres.

If the condenser under test has a higher capacity than the maximum of the wave-meter condenser, it should be placed in series in the circuit.

Let C be the capacity of the wave-meter condenser before the condenser of unknown capacity is inserted, and C_1 the capacity afterwards; then if C_x be the actual capacity of the added condenser,

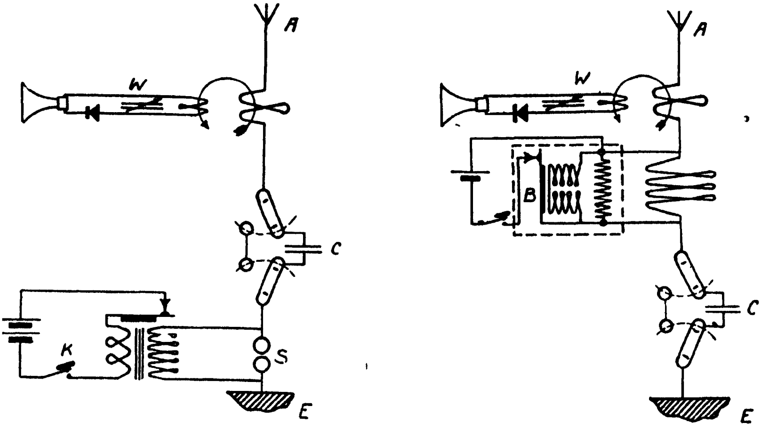
$$\frac{1}{C}=\frac{1}{C_1}+\frac{1}{C_x},$$

and

$$C_x=\frac{CC_1}{C_1-C}.$$

The connecting leads to the condenser under test should be short and thick, in order to keep down the added self-inductance. With most wave-meters this will be negligible compared with the inductance of the wave-meter coil.

The Effective Capacity of an Aerial.—To measure the effective capacity of an aerial, excite the aerial by means of an ignition coil K and spark gap S, inserted at the earthed end (Fig. 201 (*a*)), or else by a shunted buzzer B, if it contains an inductance coil (Fig. 201 (*b*)); and by means of a wave-meter W, held near the aerial, measure the natural wave-length λ. Then insert a known capacity C, as near the earthed end as possible, and measure the new wave-length λ_1.



(*a*) (*b*)

FIG. 201.—Measurement of the Effective Capacity of an Aerial. (*a*) Using Ignition Coil Excitation. (*b*) Using Buzzer Excitation.

Then the effective capacity of the aerial

$$C_A = C \times \frac{\lambda^2 - \lambda_1'^2}{\lambda_1^2}.$$

If the capacity C is continuously variable and calibrated, it may be altered until $\lambda_1 = \cdot 707\lambda$, when, arising from the wave-length formula,

$$C_A = C.$$

CHAPTER X

THE MEASUREMENT OF INDUCTANCE

The "Henry."—The Anderson Bridge Method.—The Anderson-Fleming Bridge.—The Fleming-Clinton Commutator used with Inductance Bridge.—Slide-Wire Inductance Bridge.—Inductance Bridge with two Sliders.—Slide-Wire Bridge calibrated in Inductance Units.—The "Drop in Potential" Power Method.—The Inductance of a Transformer;—of an Alternator.—A Resonance Method for Inductances of several hundred Henrys.—The Harmonic Effects in the Resonance Method.—A High-Frequency Method for small Inductances of a few Microhenrys.—The Unknown Inductance inserted in a Wave-Meter Circuit.—The Effective Inductance of an Aerial.—The Measurement of Mutual Inductance.—The Campbell Variable Mutual Standard.—Coupled Circuits.—The Coefficient of Coupling.—Its Significance.

THE practical unit of inductance, the "henry," is that degree of storing up of magnetic energy which would be possessed by an electric circuit of one turn, if a variation in it of one ampere per second were to produce an E.M.F. of one volt. The working unit for high-frequency currents is the "microhenry," the absolute electromagnetic unit the "centimetre," and there are 10^9 centimetres in one henry.

The Anderson Bridge.—The Anderson method for measuring inductances, shown in Fig. 202, is useful over a wide range. If P, Q, S are three arms of a Wheatstone bridge, the fourth arm RL being the coil whose inductance L it is required to measure, first establish a balance for direct currents, using an ordinary D'Arsonval galvanometer, so that on closing K_B and then K_G the galvanometer G shows no deflection. Then, if R is the resistance of the inductance coil,

$$\frac{P}{Q} = \frac{S}{R}, \text{ and } R = \frac{SQ}{P}$$

Now if we close the two circuits in the opposite order by first pressing the galvanometer key K_G and then the battery key K_B, the galvanometer will give a momentary kick. This will be due to the self-induction of the coil L, creating a back E.M.F. in the circuit in consequence of the rise of current passing through it, thus disturbing the balance of potential difference in the bridge until the current finally reaches its steady value. The bridge is therefore balanced a second time by inserting a plug resistance box Z, and condenser C, in the galvanometer circuit by means of a switch, and adjusting them until the galvanometer ceases to give any kick.

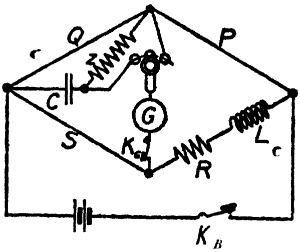


FIG. 202.—The Anderson Inductance Bridge.

When this condition is obtained

$$L = C\{Z(R + S) + RQ\}.^1$$

The Anderson-Fleming Bridge.—A useful modification by Fleming is shown in Fig. 203. For the inductive balance a telephone replaces the galvanometer, and a buzzer interrupted direct current, or an alternating current, replaces the steady direct current.

The galvanometer, however, is preferable for measurements of iron-core inductances, as, due to the iron core, it is often impossible to adjust so as to get a silent point on the telephone, and difficult sometimes even to decide when the buzz is a minimum.

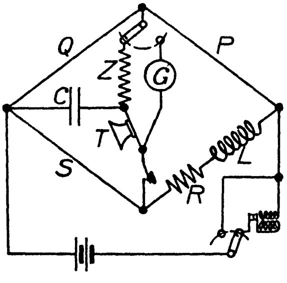


FIG. 203.—The Anderson-Fleming Inductance Bridge.

R may consist simply of the resistance of the inductance coil, when the inductance is small, or of this resistance plus a series resistance, when the inductance is high. The range for a bridge having 1000 ohms as the highest resistance used in any branch of the circuit, may be taken as from 3 henrys

---

[1] For proof see Fleming's *Handbook for the Electrical Laboratory and Testing Room*, vol. ii. p. 194.

for a condenser capacity of 1 microfarad, down to 50 microhenrys for a condenser capacity of ·01 microfarad, the resistances being adjusted to suit.

A Commutator-Bridge Method.—A special design of Fleming-Clinton commutator can be used with the Anderson method to produce a steady galvanometer deflection. Fig. 204 shows the commutator laid out flat. It consists of two pairs of interleaved and insulated wheels, mounted on a common shaft and motor-driven, a separate brush being fitted for each wheel. When the two brushes come on the common portion of the double wheel A, the galvanometer circuit is made; this is followed by the brushes on the double wheel B completing the battery circuit; then the wheel A breaks the galvanometer circuit, and finally the wheel B breaks the battery circuit. This sequence is repeated many times per second. The galvanometer is thus able to sum up all the kicks on the make of the battery current, but none of those which occur on the break, and thus is able—providing the commutator runs at constant speed—to give a constant deflection in one direction. The wheels I do not carry current, but act as insulated supports for the brushes when they pass from one projecting spoke of A or B to the next.

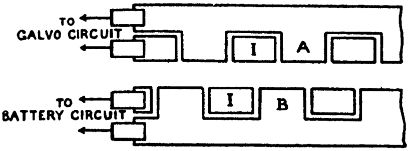


FIG. 204.—Fleming-Clinton Commutator for Use with Inductance Bridge.

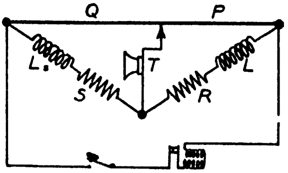


FIG. 205.—A Single Slide-Wire Bridge.

Slide-Wire Inductance Bridges.—A slide-wire method of measuring inductances by comparison with a standard, would appear at first sight to have advantages as regards simplicity of operation and ease of adjustment, but to obtain a true balance is on the contrary often a tedious business, iron-core inductances which vary in value with the strength of the current passing through them being especially difficult to test.

If R and L (Fig. 205) are the resistance and inductance of the coil under test, L_s an inductance standard, and S an adjustable resistance, then the required relation for both non-inductive and inductive balance is that $\frac{L}{L_s}=\frac{R}{S}=\frac{P}{Q}$. Then for any given value of S the slider is moved on the slide wire PQ until a minimum of sound is heard in the telephone. Then another value of S is tried, and the best balance again obtained, this operation being repeated until a value of S is found at which no sound is heard in the telephone, when the bridge will be in true balance, and $L = L_s \times \frac{P}{Q}$.

A method devised by the author which speeds up this test makes use of two slide wires, as shown in Fig 206, the resistance of the wire SR being large compared with the resistances of the inductance coils L and L_s. If the resistances of L and L_s can be neglected, then for any symmetrical position of the sliders on the two wires the bridge will be in balance for steady currents, so that the only operation required to balance for transient currents would be to move both sliders symmetrically in the same direction until no sound was heard in the telephone. But as L_s and L have some resistance, the operation just described does not result in perfect silence, and must therefore be followed by a final independent adjustment of the two sliders to correct for this.

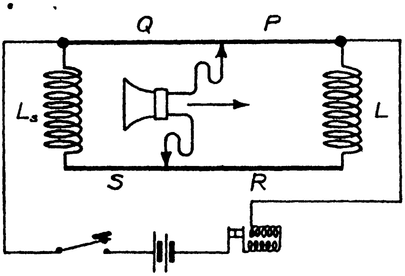


FIG. 206.—A Double Slide-Wire Bridge.

A method used for rough work, which employs one slide wire only, is to calibrate the wire PQ so that it reads direct in inductance units, by employing a fixed standard L_s, and substituting several standards at L, noting the point of balance on the wire for each inductance tested and marking it accordingly. As no provision is made in such a bridge for balancing resistance, the telephone will only in exceptional cases be silent at the best adjustment.

Measurement of Power, by Drop in Potential.—The inductance of a winding having an iron core and used in a power circuit, such as the L.F.I.C. inductance of the Marconi $1\frac{1}{2}$-kw. set, is best determined under working conditions, that is with the working current flowing through it at the working frequency. The inductance can then be calculated from the measured fall of potential in the winding as shown by an electrostatic or other suitable A.C. voltmeter. If with a given current I, at a frequency *n*, there is a fall of potential V across the inductance L (Fig. 207), which has a resistance R, then

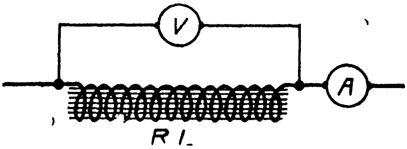


FIG. 207.—The Power Method of measuring Inductance.

$$I = \frac{V}{\sqrt{R^2 + (2\pi n L_{\text{hrys.}})^2}};$$

and if R is negligible compared with $2\pi nL$, as it generally is, then

$$L_{\text{hrys.}} = \frac{V}{2\pi n I} \text{ approximately.}$$

If an inductance coil has a potential drop across it of 300 volts when passing a current of 1 ampere at 50 cycles, the value of inductance will be roughly 1 henry.

Transformer Inductance.—To measure the inductance of a transformer under "no-load" conditions, the secondary is left open-circuited and current at the working frequency is delivered to the primary, that value being noted which gives the working P.D. between the terminals; then the inductance is found from the last formula.

To obtain the inductance under "load" conditions, proceed as follows:—

(1) Measure the ohmic resistance of the primary winding.

(2) Measure the ohmic resistance of the secondary winding, and divide it by the square of the transformation ratio (see p. 36) in order to find its equivalent value in the primary circuit.

(3) Add the two primary circuit values together to obtain the effective ohmic resistance R of the transformer.

(4) Short-circuit the transformer secondary, and, employing a regulating resistance, pass the full-load current I, at the correct frequency *n*, through the transformer primary.

(5) Measure the terminal potential V.

Then L, the effective transformer inductance, can be found from the formula which includes R given above.

Alternator Inductance.—To measure the inductance of an alternator, excite the machine by connecting the field windings to the normal D.C. supply, then with the armature stationary pass the full lead current through it at the correct frequency, noting the P.D. between the slip rings. Then work out the inductance as above. Repeat this operation with the armature moved through a small angle, and continue to repeat it until the armature will have been turned through a sufficient angle for its winding to have travelled more than one pole pitch, and therefore through the complete range of field strength. Then distinct minimum and maximum values will have been obtained (see Fig. 208), and the inductance of the alternator should be stated to vary within these limits.

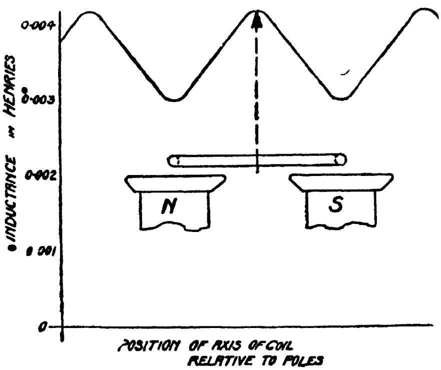


FIG. 208.—The Variable Inductance of an Alternator.

A Low-Frequency Resonance Method.—If the inductance of a coil is very high, say several hundred henrys, such as the secondary of a 10″ induction coil, or the secondary of a power transformer, it can be measured by loosely coupling it to a neighbouring circuit carrying a current of known low frequency, and establishing a condition of resonance by the aid of an adjustable standard condenser C_s and a series low-resistance telephone T (Fig. 209). C_s is varied until the noise in the telephones is a maximum, and the capacity which establishes this condition is noted. Then *n*, the frequency per second of the inducing current, being known, and the resistance of the inductance coil being negligible compared with its total impedance—which is usually the case,—and the impedance of the telephone compared with that of the coil also being negligible,

$$n = \frac{1}{2\pi\sqrt{L_{\text{hrys.}} C_{\text{farads}}}}$$

and $$L_{\text{hrys.}} = \frac{10^6}{4\pi^2 n^2 C_{\text{mfds.}}}$$

As an example, if $n = 100$, and $C = \cdot 01$ mfd., then L will be roughly 250 henrys.

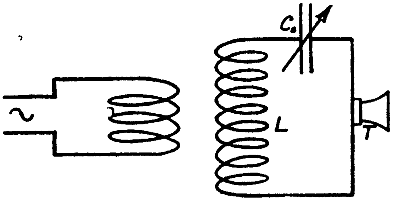


FIG. 209.—A Low-Frequency Resonance Method.

It will be found that as the condenser is diminished in capacity below the value required for tuning to the frequency of the inducing current, the circuit will tune successively to the odd harmonics of 3, 5, 7, 9, etc. times this frequency, the telephone note gradually rising in pitch. Fig. 210 represents the inductance coil and condenser opened out, and the wave-forms of the related resonating frequencies, each of which has a potential node at the centre of the inductance coil and an antinode at the condenser. When tuning to the fundamental appears to be flat, the circuit may be tuned alternately to one of these harmonics, the frequency of which will be given by multiplying the fundamental frequency by the order of the harmonic. Thus, the lowest note obtainable will be the fundamental; the next note to it will be the third harmonic, which will have three times the frequency; the next note five times the frequency, and so on. If there is any doubt as to the correct pitch of the fundamental frequency, a telephone fitted with a shunt suffi-

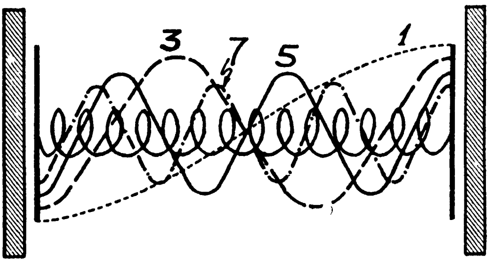


FIG. 210.—The Harmonics which show up in the L F. Resonance Method.

ciently large to carry the full current may be inserted in series in the primary inducing circuit, whence it can be heard.

A High-Frequency Resonance Method.—Small inductances of a few microhenrys are most easily measured by a high-frequency resonance method, as shown in Fig. 211, where L is the unknown inductance, C_s a standard condenser, B a shunted buzzer, and W a wave-meter circuit with crystal detector and telephone. On closing the buzzer circuit switch Z, the wave-meter coil picks up from L, and resonance is established by varying the wave-meter condenser C_w until the buzz in the telephone reaches a maximum. Then the wave-length corresponding to this setting of C_w being known, and C_s being known, L can be found from the formula

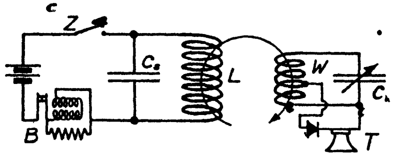


FIG. 211.—A High-Frequency Resonance Method.

$$\lambda_{\text{metres}} = 1885\sqrt{L_{\text{mhrys.}} \times C_{\text{mfds.}}}$$

or

$$L_{\text{mhrys.}} = \frac{\lambda^2_{\text{metres}}}{3{\cdot}55 \times 10^6 \times C_{\text{mfds.}}}.$$

Thus a standard capacity of ·01 mfd. will be suitable for measuring a range of inductances from 2·5 mhrys. to 38 mhrys., if the wave-meter has a range from 300 metres to 1200 metres.

Alternatively the inductance can be inserted in the wave-meter circuit and measured, if the wave-meter inductance is known, and the condenser is also calibrated in capacity (see p. 296 and Fig. 278).

This method requires a source of high-frequency current in a neighbouring circuit which gives a wave-length reading, λ, high up on the scale of the wave-meter condenser.

Then if L be the inductance of the wave-meter, and L_1 the inductance to be measured, and if C and C_1 be the respective capacities of the wave-meter condenser when it is tuned to λ without and with L_1 in circuit, when the wave-meter is in tune

$$\lambda^2 = 4\pi^2(L + L_1)C_1 = 4\pi^2 LC,$$

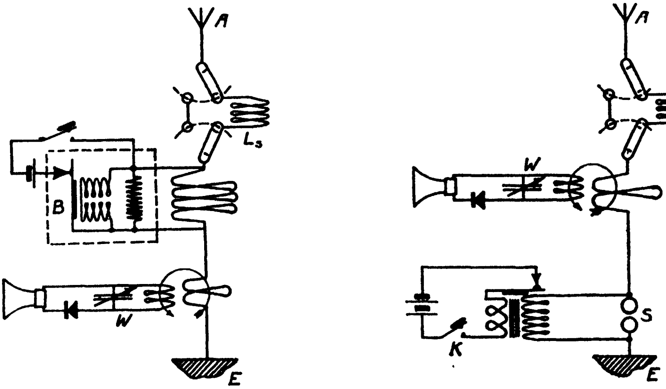
and

$$L_1 = L\left(\frac{C}{C_1} - 1\right)$$

The Effective Inductance of an Aerial.—The effective inductance L_A of an aerial can be measured by means of a standard inductance and a wave-meter.

If the aerial already contains an inductance coil, it can be excited by means of a shunted buzzer B, as shown in Fig. 212 (*a*); if it does not, then an ignition coil excitation K can be used, with a spark gap S, inserted near the earthed end of the aerial, as shown in Fig. 212 (*b*).

By means of the wave-meter W, held near the aerial, find the natural wave of the aerial λ; next insert the known inductance L_S, and find the value of the new wave-length λ_1. Then from the two wave-length equations it can be shown that



(*a*) (*b*)

FIG. 212.—Measuring the Effective Inductance of an Aerial: (*a*) by means of a Buzzer Method; (*b*) by a Spark Method.

$$L_A = L_S \times \frac{\lambda^2}{\lambda_1^2 - \lambda^2}.$$

The Measurement of Mutual Inductance.—If two coils, or electric circuits, are so close to each other that the magnetic field produced by a current in one of them extends into or through the other, the measure of that part of the total magnetic flux which thus gets linked with the second coil or circuit is called the Coefficient of Mutual Induction of the two coils or circuits, and is denoted by the letter M. The unit is the "henry," and consists of 10^8 lines of linkage in one of the circuits, as a result of a current of one ampere in the other.

Let L_1 = the inductance of one closed circuit by itself, and
L_2 = the inductance of the other, the two circuits being widely separated.

If a current is passed through *both* circuits in series, the term for mutual inductance must occur *twice* in the expression for total inductance, so that if

L_3 = the inductance of the two circuits when connected so that their two magnetic fields assist, and
L_4 = their inductances when the fields oppose;

then $L_3 = L_1 + L_2 + 2M$, and $L_4 = L_1 + L_2 - 2M$;

from which $$M = \frac{L_3 - L_4}{4}.$$

L_3 and L_4 can be measured by that method among those already described which is considered most suitable for the purpose, or M may be measured by direct comparison with a standard mutual inductance consisting of two coils whose magnetic coupling with each other can be varied, the resulting change in M for different settings of the axes of the coils having been previously found by measurement or by calculation.

The Campbell Variable Mutual Standard (Fig. 213 (*a*)) is constructed on this principle.

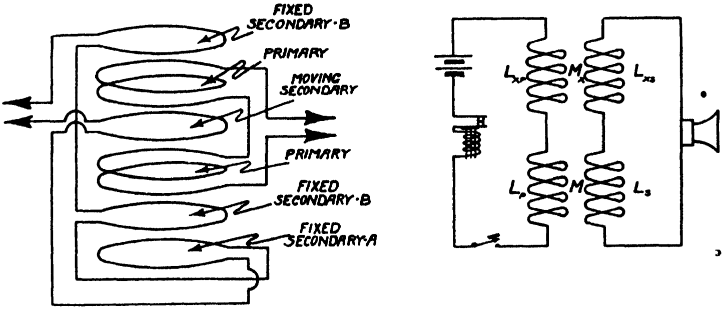
To measure a value of M within its range— ·2 microhenry to 1100 microhenrys on one type, and 2 microhenrys to 11,000 microhenrys on another—connections are made as shown in Fig. 213 (*b*), where L_P and L_S are respectively the primary and secondary of the standard, and L_{XP} and L_{XS} the primary and secondary of the unknown, connected in opposition to the standard.

Then if the standard mutual inductance is varied until there is silence in the telephone, $M_X = M$, where M is the scale reading of the standard.

If available, a source of A.C. supply can be used in place of the buzzer interrupter, and a vibration galvanometer in place of the telephone.

Coupled Circuits.—But the most interesting and important cases involving mutual inductance with which we have to deal are the "coupled" circuits, in which energy is conveyed from one to the other solely by means of the mutual field.

When the primary current is increasing, it is the mutual field due to the primary current which expends itself in giving rise to an induced current in the secondary circuit, and if the energy of this secondary current is not used up in the secondary circuit its mutual field reacts back on the primary circuit, at a rate determined by the natural period of oscillation of the secondary circuit and the period impressed by the primary circuit, so that if the primary is fed with alternating current there is a continual interchange of energy between the two circuits.



(*a*) (*b*)

FIG. 213.—The Campbell Variable Mutual Standard.

(*a*) Diagram showing Arrangement of Coils ; (*b*) the Use of the Standard for measuring an Unknown Mutual Inductance.

If the period impressed by the primary circuit is the same as the natural period of the secondary circuit, a state of resonance is established, and the secondary circuit feeds back its energy to the primary at the same rate as the primary feeds out its energy to the secondary, but the two operations are out of step.

The Coefficient of Coupling is given by the ratio

$$\frac{M}{\sqrt{L_P \times L_S}} = k,$$

and is really the fraction by which the inductance of either circuit is diminished or increased due to the weakening or strengthening of its magnetic field, as a result of the inductive action of the other circuit.

Thus, when the primary circuit is *giving out* energy its effective inductance is $L_P(1-k)$, and when it is *receiving* energy its effective inductance is $L_P(1+k)$.

The secondary circuit also under similar conditions will have effective inductances $L_S(1-k)$ and $L_S(1+k)$.

As an illustration, in the test for the measurement of very high inductance (page 216), there are two positions of the condenser which should give resonance to the fundamental note of the primary circuit, corresponding to the values $L(1-k)$ and $L(1+k)$ of the coil under test, but by keeping the coupling weak, or "loose," and therefore the value of k very small, the two points of resonance are brought so close together that they become indistinguishable.

But suppose the current energy induced in the secondary circuit is used up as fast as it is produced, then it will not be available for reacting or "surging" back on the primary circuit, and the magnetic field will be represented by the field produced by the primary minus the mutual field used up by the secondary, and the inductance of the primary circuit therefore by $L_P(1-k)$.

In the case of the standard low-frequency closed iron-core transformer, the endeavour is to make $k=1$ by coupling the circuits as "tight" as possible, so that *the whole* of the primary energy may be made available for the use of the secondary circuit, with the result that the effective inductance of the primary winding measured on load falls to a negligibly small value.

CHAPTER XI

THE MEASUREMENT OF FREQUENCY

Machine Frequencies.—The Frahms Method.—Stroboscopic Methods.—Drysdale's Roller Stroboscope.—A Tuning-Fork controlled Shutter.—The Frequency of Alternating Currents.—The Hartmann and Braun Frequency-Meter.—Method used to double its Range.—The Principle of Induction Frequency-Meters.—The Westinghouse Instrument.—The Weston Instrument.—The Use of a Thin Filament Lamp—Or Neon Tube.—An Oscillograph Method.—A Gehreke Oscilloscope Method.—The Behaviour of Frequency-Meters when the Alternations are not Sinoidal.—Spark Frequency.—Fleming Tape Record Device.—The Marconi Dictaphone Method.—Fleming Photographic Method.—The Measurement of Oscillation Frequency.—The Campbell Spark Counter.—Maxwell Bridge Method for indicating any Change in Speed of Revolving Mirror.—Roller Stroboscope and Tuning-Fork Control.—Photographs of Spark Trains.—The Measurement of Wave-Length.—With Reference to a Standard Velocity of Propagation.—"Lecher Wire" Circuits.—The Commercial Wave-Meter.—Wave-Meter Calibration for Short Wave-Lengths up to 300 *Metres.—Wave-Lengths of* 300 *Metres to* 1500 *Metres, and of* 1000 *Metres to* 3000 *Metres.—The Spark-Counter Method best for all Wave-Lengths above* 1500 *Metres.—Buzzer Oscillating Circuits for Test Room Use.—The Tuning Tester.—A Comparison of the Resonance Method with the Spark-Counter Method when there are Coupled Waves in the Oscillating Circuit.*

Machine Frequencies.—The speed of a machine is usually stated in terms of the number of revolutions it makes per minute—that is, in terms of frequency—and is generally measured by speed counter and stop-watch, the counter consisting of a set of gear wheels worm-driven from a spindle the end of which is pressed firmly into the centre hole of the machine shaft, or by a direct reading tachometer, in which the shaft movement is transmitted by a belt or friction drive to a form of centrifugal pendulum resembling a governor, the control springs of which work an indicator pointer.

But some small machines have their speed affected by using a counter or tachometer, and for other reasons it may be inadvisable sometimes to use them with large machines. For such cases the Frahms method may prove suitable. A toothed wheel is fitted to the rotating shaft, and the teeth give a mechanical vibration to an iron support carrying a number of tuned indicating reeds, causing that one to vibrate strongest which has the same period. Or again, a light attachment or commutator may be fixed to the shaft, which completes the electric circuit of a frequency-meter once per revolution.

Stroboscopic methods are also used which work on the following principle:

Supposing a disc X (Fig. 214), having a number of concentric star designs, is fixed on the end of the running shaft, the stars all having a different number of points, say from four upwards. Let this disc be viewed by an observer at Z, through another slotted disc, Y, running at a known constant speed. Then the slotted disc will act like a shutter, only exposing a view of X to Z so many times per revolution, depending on the number of slots in Y. In the interval between slot K leaving the line of vision and slot H entering it, the outer star may have moved from A to B, which is not symmetrical in relation to A, and this star will therefore appear to have moved backward. The inner star, under similar conditions moving from E to F, will appear to have moved forward, while the middle star, moving from C to D, which is symmetrical with C, will present no change apparent to the eye, and thus will

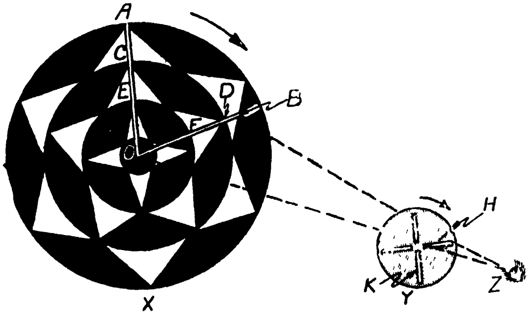


FIG. 214.—A Stroboscopic Disc and Shutter.

appear to have stood still. This effect is due to the disc X travelling $\frac{1}{5}$th of a revolution in the same time that the disc Y travels $\frac{1}{4}$th of a revolution, and the speed of X will therefore be $\frac{4}{5}$ × speed of Y, or

$$\text{Speed of shaft} = \frac{\text{Number of slots in shutter} \times \text{Speed of shutter}}{\text{Number of points in stationary star}}.$$

Suppose it is not possible to fix such a disc X on the end of the running shaft, then if a single radial line is marked on it in chalk, under the same running conditions as just described there will appear to be five single lines when the shaft is viewed through the slots in disc Y, and

$$\text{Speed of shaft} = \frac{\text{Number of slots in shutter} \times \text{Speed of shutter}}{\text{Apparent number of single lines}}.$$

But the relation between the two speeds need not be a simple one such as 4 to 5. If four revolutions of Y take place in the same time as five revolutions of X, then the lines seen on the shaft will be all single. But if four revolutions of Y take place in the same time as $5\frac{1}{2}$, $6\frac{1}{2}$, $7\frac{1}{2}$, etc., revolutions of X, then 5, 6, 7, etc., double lines will be seen on the shaft, or if the relation is 4 to $5\frac{1}{3}$, $6\frac{1}{3}$, $7\frac{1}{3}$, etc., the lines will be triple —the multiplication of the lines depending on the denominator of the fraction. If it is possible, however, to vary the speed of Y and still know its value, it is decidedly better to do this in order to make the lines remain single.

Drysdale's method (Fig. 215) is to revolve the disc Y by a roller drive on the surface of a cone AB, which has the same diameter at the big end as the disc Y, and is driven at constant speed. According to the position at which Y is set on AB, its speed will be equal to or less than that of AB, by an amount which is indicated on a scale mounted parallel to the axis of the cone.

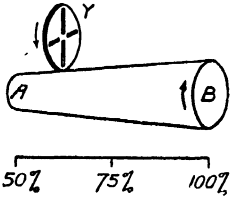


FIG. 215.—The Drysdale Roller Stroboscope.

If there appear to be five double lines on the shaft X when the disc Y is set at a given position on the cone, they will be reduced to five single lines by reducing the speed of Y 10 per cent—

that is, by shifting Y to a position where the diameter of the cone is 10 per cent less than before.

$$\text{Then speed of X} = \frac{\text{Number of slots in shutter} \times \text{Speed of cone} \times \text{Percentage shown on scale}}{\text{Apparent number of single lines}}.$$

The rotary disc Y may be replaced by a tuning-fork vibrating at a known frequency (see Fig. 216), the prongs of which carry shutters S, provided with slits which open twice per period, the fork being set in vibration by means of an interrupted direct current passing through the winding W and the contact C on the fork. As the rate of opening and closing the shutter is fixed, the disc X should be provided with many suitable concentric stars in order to allow the tuning-fork to be used for measuring speed over a wide range.

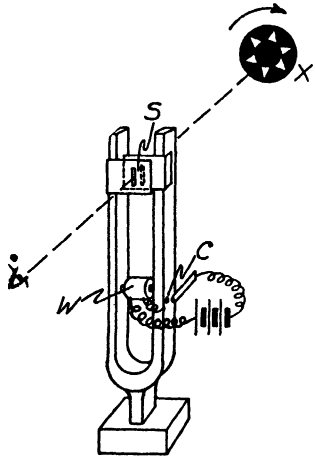


FIG. 216.—An Electrically Controlled Tuning-Fork working a Shutter.

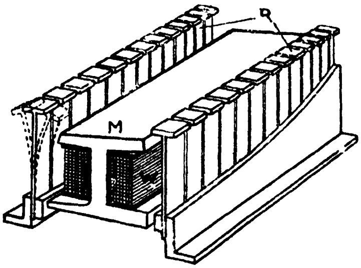


FIG. 217.—The Hartmann and Braun Frequency Meter.

The Frequency of Alternating Currents, stated in cycles per second, is best measured in practice by means of tuned reeds.

In the Hartmann and Braun instrument two parallel rows of steel reeds R (Fig. 217), with flat whitened ends for indicating purposes, all tuned to different frequencies, are acted on by an oblong electromagnet M, which is placed between them, and is excited by the alternating current the frequency of which it is required to measure. In the diagram a section has been taken through the end of the magnet winding in order to expose more detail.

In the Everett-Edgcumbe instrument the reeds surround a circular electromagnet.

A method used to double the range of the reeds is illustrated in Fig. 218. If AB is the line of zero current, every time the alternating current grows from zero, whether positively or negatively, the magnet exerts a pull on the reeds, so that they are attracted twice per cycle. Now if this zero line is shifted down to the position CD, by superposing a direct current of value AC, which exactly neutralises the field due to the negative part of the alternating current when it is at its maximum, then the variations of flux in the magnet will all be on one side of the zero, and there will in consequence be only one pull by the magnet per cycle. Thus a reed which indicates 100 cycles when pulled twice per cycle by the electromagnet, will be suitable for indicating 200 cycles if the magnet has both an A.C. and a suitable D.C. winding, so that it pulls the reed only once per cycle.

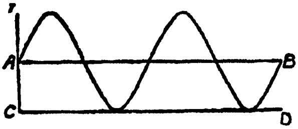


FIG. 218.—The Use of a Direct-Current Winding for doubling the Range of a Reed Frequency Meter.

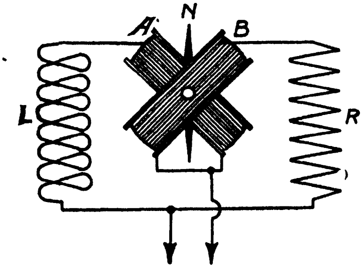


FIG. 219.—The Principle of Induction Frequency Meters.

Another method of measuring frequency makes use of the fact that the current in a circuit connected to a constant voltage A.C. supply will be constant at any frequency if the circuit only contains non-inductive resistance, but if it contains inductance, the resistance being negligible, the current will be given by the expression

$$I_{\text{r.m.s.}} = \frac{V_{\text{r.m.s.}}}{2\pi n L},$$

that is, it will be inversely proportional to the frequency. A and B are two coils with axes at right angles (Fig. 219), which are so connected in parallel that when current flows through the windings, the independent influence of each magnetic field on a needle N, pivoted at the common centre of the two coils, is to swing it round in opposite directions. If an inductance coil L is connected in series with A, and a resistance R in series with B, then values of L and R can be chosen such that, when current of a given frequency is passed through the two coils A and B, the position of equilibrium for the needle will be midway between A and B. For any other frequency the current through A will be less or greater than through B, and the needle will take up a position nearer to or farther away from the coil A, and its movement can therefore be calibrated to indicate the frequency of the supply current.

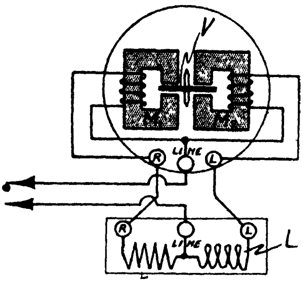


Fig. 220.—The Westinghouse Frequency Meter.

In the Westinghouse instrument, the place of the coils A and B is taken by two electromagnets M_1 and M_2 (Fig. 220), and the place of the needle by an aluminium disc V, which floats between the jaws of the magnets.

The reaction between the alternating magnetic flux due to one magnet, and the eddy currents set up by it in the disc, tend to rotate the disc. This movement is opposed by the reaction due to the field of the other magnet. The force causing movement thus depends on the difference in the field strengths of the two magnets, one of which, due to the series inductance coil L, will be much more affected by frequency than the other. The disc is so shaped that it moves out of the field of the stronger magnet as it rotates, and so can take up a final position of equilibrium, instead of continuing to rotate under the influence of the difference of the two driving torques.

A diagram of the Weston frequency-meter is shown in Fig. 221. While this instrument also works on the principle already described, the special arrangement of its circuits, which results in a very open scale, merits remark. A light needle N takes up a position of equilibrium determined by the difference of the torques exerted by the current through the coil A, in series with the inductance winding L, and the current through the coil B, in series with the non-inductive resistance R.

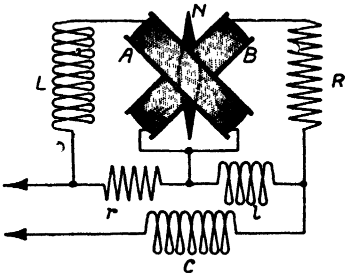


Fig. 221.—The Weston Frequency Meter.

But this difference is accentuated by the bridge method of connections used, which can be better understood by reference to Fig. 222. As the frequency increases, not only does less current flow through the branch LA, but due to the increased impedance of *l*, more current flows through the branch RB, so that change of frequency affects both coils instead of only one, which results in greater movement of the needle and therefore a more open scale.

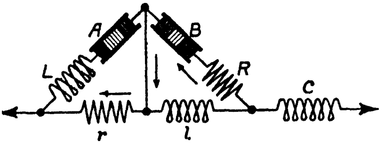


Fig. 222.—The Weston Bridge Circuit.

The inductive coil C is a choke designed to damp out the higher harmonics, as all instruments which depend on the above principle are likely to read high if the wave-form is not truly sinoidal.

In case a frequency-meter is not available, it may be possible to apply one of the various methods described below.

If the speed of the alternator can be measured and its general design is known, then

$$n = \frac{\text{Speed of alternator in r.p.m.} \times \text{Number of pairs of poles}}{60}.$$

If a thin filament lamp—that is, one which responds quickly in brilliancy to variations in current and therefore will dim twice per cycle—is connected to the A.C. supply, and its light is thrown on a stroboscopic disc rotating at a known speed, and marked with a number of equally spaced radial lines, such a disc will appear to be stationary when

$$n = \frac{\text{Speed of disc in r.p.m.} \times \text{Number of stationary lines}}{2 \times 60}.$$

If one line only is marked on the disc, then the rule must be modified to read " number of apparent stationary lines." In place of the lamp a neon tube could be used, excited through a suitable transformer, the primary of which would be connected in the alternator circuit.

The Duddell oscillograph (see p. 168) is fitted with two vibrators. One may be connected to an A.C. supply of known frequency, and the other vibrator to the supply of unknown frequency. The two wave-forms can then be directly compared, either by observation in a revolving mirror or by photographing them in the usual way on a dropping-plate. Fig. 223 shows an oscillogram of an alternating current of 150 cycles used to measure the natural frequency of a circuit excited from a battery by means of a commutator. The unknown frequency works out as 4000 cycles.

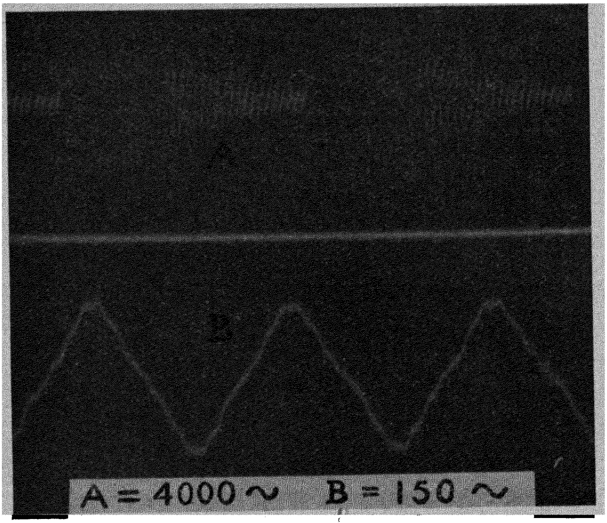
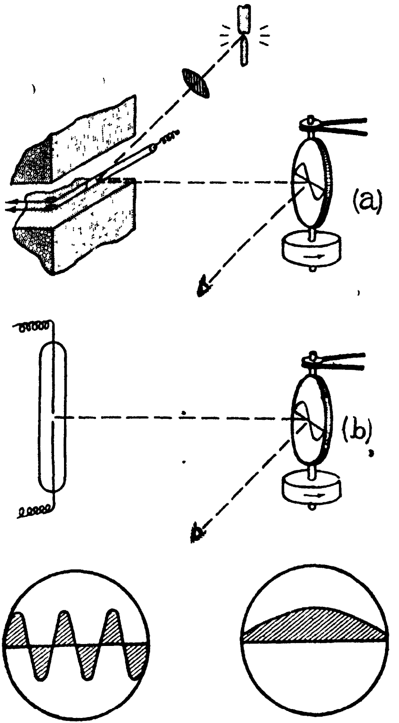


FIG. 223.—A Full-Scale Oscillogram showing a Current having a Frequency of 4000 Cycles, compared against one of 150 Cycles.

Or again, a single rotating mirror used in conjunction with an oscillograph (Fig. 224 (*a*)), or with a Gehrcke oscilloscope

(Fig. 224 (*b*)), provides yet other means of determining frequency.



(*c*) (*d*)

FIG. 224.—(*a*) Oscillograph and (*b*) Oscilloscope Methods; (*c*) and (*d*) Wave-Forms in a Single Rotating Mirror.

The oscilloscope is a sealed glass tube evacuated of air, but containing nitrogen at 8 mm. pressure, which is fitted with two aluminium rod electrodes in line, but separated by a small gap.

When a voltage is applied to the oscilloscope, as soon as it exceeds a certain value a purple brush appears, which extends from the gap for a distance along each electrode, proportional to the potential of that electrode.

If the potential is alternating, and the brush which results is examined in a rotating mirror, it will be seen to be spread out into a wave-form curve, as shown in Fig. 224 (*b*).

As the mirror speeds up from rest, it will in time reach a point at which it shows a stationary image of several alternations (Fig. 224 (*c*)). If the speed is further increased, the image will once more move across the mirror, until that speed is reached which gives another stationary image, but with fewer alternations. When the mirror finally shows a stationary image of a half-cycle only (Fig. 224 (*d*))—the angular width will be less than 180° of phase owing to the limitations of the test—then it will have travelled in the same time through 90 angular degrees, and therefore it will have half the angular speed of the alternating current, and

$$n = 2 \times \frac{\text{Speed of mirror in r.p.m.}}{60}.$$

A mirror speed of 4000 r.p.m. on this basis corresponds to 133·3 cycles per second.

If a multiple cycle image is used to measure higher frequencies, or a mirror having four or six faces—which, however, has the disadvantage of still further reducing the angular width of the image—then

$$n = 2 \times \frac{\begin{matrix}\text{Speed of mirror}\\ \text{in r.p.m.}\end{matrix} \times \begin{matrix}\text{Number of}\\ \text{stationary}\\ \text{half-cycles}\end{matrix} \times \begin{matrix}\text{Number of}\\ \text{faces of}\\ \text{mirror}\end{matrix}}{60}.$$

It seldom happens that the wave-form given by an alternating current machine is truly sinoidal. In order that it should be so the field cut by each armature coil as it revolves should vary in a sinoidal manner. Badly shaped pole shoes, and the effect of the armature teeth forming the slots in which the winding is embedded, interfere with the attainment of such a condition. Fig. 225 illustrates a case in point.

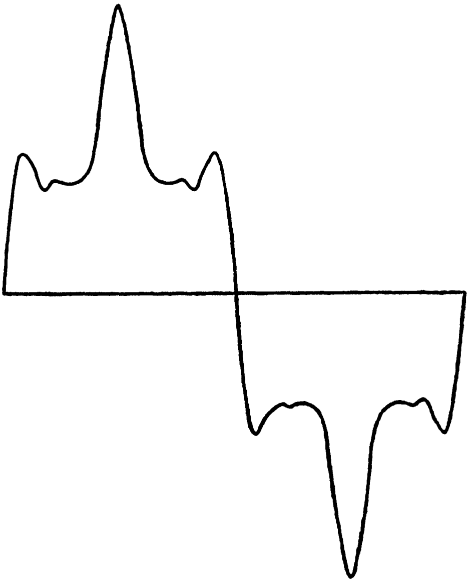


Fig. 225.—Compound Wave-Form Curves.

All such wave-form curves can be analysed into a number of superposed sinoidal curves of different frequencies and amplitudes, harmonics of the main frequency,—Fig. 226 representing the component curves for the wave-form in Fig. 225.

In a frequency-meter which acts by resonance each of these harmonics will try to excite its own indicator, but in a frequency-meter which balances an impedance against a non-inductive resistance it is the mean magnetic field created by the compound current wave as a whole each half oscillation, in addition to the frequency, which is effective; and as it can be shown that any departure of the generator voltage from a sinoidal wave-form, whether peaky or square, results for the same R.M.S. value of the voltage in an increase in the R.M.S. current and therefore the mean magnetic field, on such wave-forms the deflections of an instrument calibrated for sine wave frequencies are likely to read high.

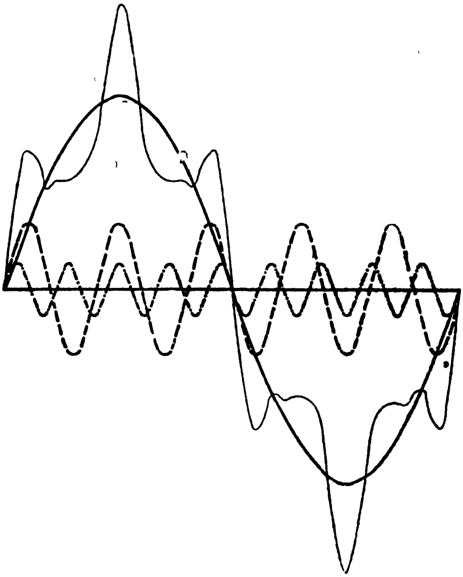


FIG. 226.—A Compound Wave-Form analysed.

The Measurement of Spark Frequency, or the Frequency of Trains of Oscillations.—In the case of a synchronous disc discharger in a properly tuned circuit, the disc, when viewed by the light of its own sparks, will appear to be stationary, and the number of sparks or discharges per second will be given by

$$n = \frac{\text{r.p.m. of disc} \times \text{Number of disc studs}}{60},$$

which should be twice the number of cycles of the alternator. If the set is not properly tuned, instead of the single discharge per stud there may be several irregular discharges per stud, or there may be no discharge at all to some of the studs, and the disc, when viewed sparking, will not appear to be stationary.

When a plain discharger is used the sparking is always more or less irregular, as it depends on several factors—the tuning of the condenser-charging circuit to the frequency of the alternator, the capacity and inductance in the discharge circuit, and the length of the spark gap.

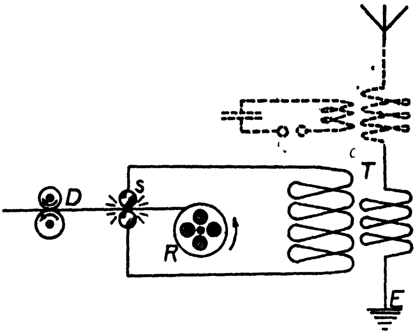


FIG. 227.—A Method of obtaining a Tape Record of Spark Frequency.

As the power in the oscillating circuit cannot be correctly calculated unless the number of spark discharges is known, one of the following methods which record the total number of sparks occurring in a given time may sometimes prove of use:

J. A. Fleming has described a method in which a Morse tape (R, Fig. 227) is run at a steady known speed by driving and jockey pulleys D, between two spark balls S connected to the secondary of a small oscillation transformer T included in the high-frequency circuit. The spark at S, which occurs every time there is a main discharge, makes a small puncture in the tape, or else can be made to mark it if the tape is first saturated with ferricyanide of potassium. The highest practical speed for a paper tape is about 17 feet per minute, and if at this speed the spark marks are spaced $\frac{1}{16}$th inch apart the spark frequency will be 54·4 per second, which is quite a low figure in practice, so that the method only has a limited application.

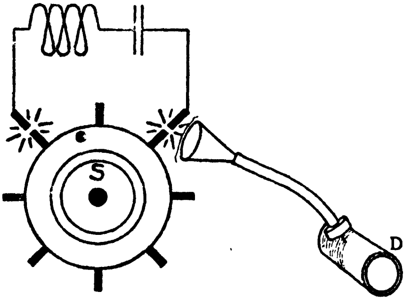


FIG. 228.—The Marconi Dictaphone Method of obtaining a Spark Record.

In the Marconi dictaphone method (Fig. 228) S is any spark discharger giving an audible note, and D a dictaphone the cylinder of which is running at a high speed. A trumpet placed near the spark is fitted to the vibrating disc and style of the recorder. Then every spark will make an impression on the wax cylinder, the speed of revolution of which must be noted. Having obtained a record, the cylinder is run again at a low speed, a transcriber with telephone replaces the recorder, and the number of spark impressions is counted. The spark frequency is then given by

$$n = \frac{\text{Spark impressions per second} \times \text{Recording speed}}{\text{Transcribing speed}}.$$

The diameter of the wax cylinder is $2\frac{3}{8}''$. It can be run satisfactorily up to 1000 r.p.m. If the spark impressions are $\frac{1}{16}$th″ apart at this speed, the spark frequency will be 2000 per second. This arrangement, therefore, will cover all working frequencies.

Fleming's photographic method is illustrated in Fig. 229. The image of the spark S passes through, and is concentrated by, the rectilinear camera lense L, on to the four-sided revolving mirror M, which is driven by clockwork W in the blackened and light-tight box B. The focus of the spark image reflected from the mirror is at X, where a sensitised plate P falls in front of a slit Z. Four series of spark images per revolution of the mirror are thrown on the plate, which by its fall down the slide prevents them superposing. The complete series of sparks which occurs during the time of one revolution of the mirror is not recorded by this method, only the sparks during four short equi-spaced intervals in that time. It allows, however, good average countings to be made. Fig. 230 shows the type of spark record made on the sensitised plate. If R is the distance in inches between the

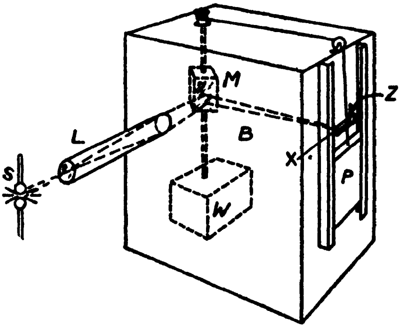


FIG. 229.—The Fleming Photographic Spark Counter.

mirror axis and the plate, the rate of movement of the focussed ray at P will be 2 × mirror speed in r.p.m. × 2πR, and if d is the mean distance between spark images on P, then the spark frequency per second—

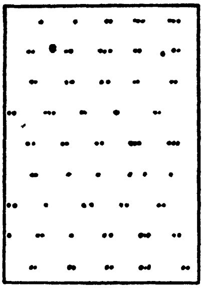


FIG. 230.—Diagram illustrating the Type of Record obtained with Fleming Photographic Counter.

$$n = \frac{2 \times \text{Mirror speed in r.p.m.} \times 2\pi R}{d \times 60}.$$

The four sides of the mirror are useful simply to provide more images, their number does not come into the expression for spark frequency.

If $R = 15''$, $d = \frac{1}{16}''$, and mirror speed $= 20$ r.p.m., then $n = 1005$ sparks per second.

The Measurement of Oscillation Frequency.—Each spark discharge in a circuit containing capacity C, and inductance L, in which the ratio $\sqrt{\frac{4L}{C}}$ is greater than the resistance R, has an oscillatory character; the condenser charge surging backwards and forwards across the spark gap and along the conductors from one side of the condenser dielectric to the other.

To count the number of oscillations in a single discharge or spark train requires a refinement of method in advance of any counting process yet discussed. Instead of dealing with phenomena which recur, say a few hundred times per second, the oscillations in each spark group may recur several *million* times per second.

Each spark image must be spread out as much as possible, so that its oscillatory character, as shown by rapid variations in brightness giving it a banded appearance, can be examined without difficulty. Clearly a photographic method is likely to give best results.

The spark counter designed by the National Physical Laboratory is illustrated in Fig. 231. An identical instrument made by R. W. Paul is used by the Marconi Company. It consists essentially of a long V-shaped camera C, having a rotating mirror M at the junction of its two sections, the sparking electrodes S at the end of one of the sections, and a slide P—which moves in front of a slot and takes a ground-glass screen or falling photographic plate—at the end of the other; the complete apparatus being mounted for rigidity on a heavy stone slab, T. The mirror is belt driven by an independent motor, and rotates on a vertical axis. It is fitted with a heavy fly-wheel and carefully balanced so that it can run with perfect safety at high speeds up to 5000 r.p.m. It is concave and has a focus at about two metres, the slide to take the plate being adjusted to the correct distance while the mirror is revolving at the working speed and the gap is sparking, using the ground-glass screen. The instrument spark gap is connected in the external high-frequency discharge circuit, and may either itself be the main spark gap, or else it may be used as an auxiliary gap in series with the main spark gap. The electrodes are of cadmium, a metal which gives a spark strong in actinic rays.

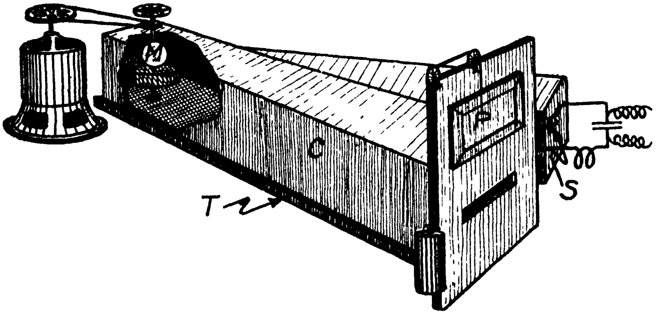


Fig. 231.—The Campbell-Paul Photographic Spark Counter.

The speed of the mirror must be kept dead constant, and must be measured with a high degree of accuracy.

Campbell's method makes use of a small commutator A, mounted on the mirror shaft, which allows a condenser to be charged and discharged in a Maxwell bridge circuit (Fig. 232). The bridge is balanced in the usual way so that the galvanometer gives no deflection. If then the speed of the mirror M varies, the balance is upset. It is maintained by using an adjustable break on the mirror shaft. Knowing the capacity of the condenser K, and the resistance of the bridge arms, the frequency of interruption of the charging current which gives a balance, and therefore the speed of the mirror, can be accurately calculated.

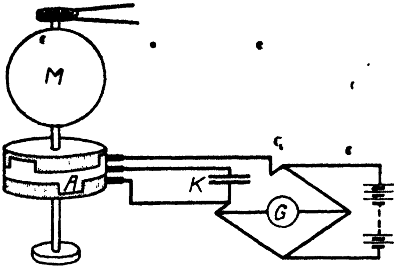


Fig. 232.—The Campbell Device for indicating Constancy of Mirror Speed.

Alternatively, the commutator can be used to interrupt a suitable supply to a frequency meter, and the mirror speed can thus be obtained direct. But the range of the speed which can be measured in this way is limited, also it can seldom be measured closer than ½ per cent.

The Marconi test room practice is therefore to use a

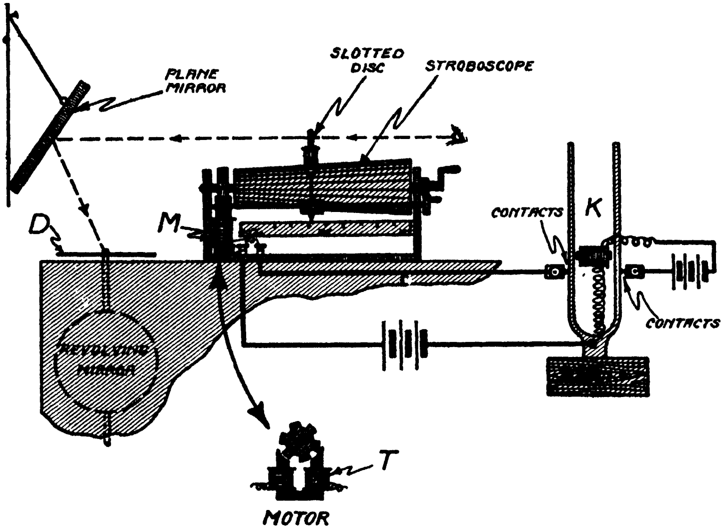


Fig. 233.—The Marconi Method for insuring Accuracy in the Measurement of Mirror Speed.

Drysdale roller stroboscope and tuning-fork (Fig. 233), which can cover the whole practical range of speed with an accuracy within 0·1 per cent. A horizontal stroboscopic disc D is fixed on the end of the mirror shaft, and its image is viewed in a plain reflecting mirror, inclined 45° above it, through the slits in a disc rolling on a cone which is driven at a constant speed by the small A.C. motor M.

The motor consists of a simple electromagnet T, and an armature which is a plain, soft-iron, toothed disc. The magnet winding is either fed from a suitable A.C. supply of known frequency, or, as in the present case, by a D.C. supply interrupted a definite number of times per second by the vibration of the tuning-fork K. The armature is run up to speed by a geared hand-drive. As it revolves the alternating or intermittent current through the magnet winding causes a magnetic pull on the teeth, either twice per A.C. cycle or once per D.C. impulse, and the disc finally settles down to that steady speed which is synchronous with the supply, just as a pendulum which is required to maintain a steady swing must have a time of vibration which synchronises with the impulses which supply it with energy.

A tuning-fork interrupting the D.C. supply to the electromagnet 100 times per second, or a 50-cycle A.C. supply, will cause the cone to run at a speed of 1000 r.p.m.

Thus, when the oscillatory circuit under test is sparking at S (Fig. 231), and the image of the spark is brought to a focus on the ground-glass screen at P, by adjusting the distance of S from M; when the speed of the mirror has been increased until the image of each spark train caught on the screen is spread out to a width which clearly shows up the individual sparks in the train—a width of from 1″ to 3″ or 4″—then a dark slide with photographic plate is inserted in the carrier at P, and the spark groups are photographed by sliding it over the aperture at a slow and uniform speed.

Fig. 234 is a half-size reproduction of spark trains having oscillation frequencies of 18,790 per second, 35,375 per second, and 137,600 per second, calculated from the following tabulated values and the formulas used with the Fleming spark counter (p. 236), and the Drysdale roller stroboscope (p. 226), two sparks occurring for each complete oscillation.

Spark photograph.	Distance mirror to plate R.	Mean Distance between sparks *d*.	Speed of cone.	Percentage setting of roller disc.	Slots in disc.	No. of points in stationary star.	Speed of mirror.	Spark Frequency.
a	202 cm.	0·84 cm.	1000 r.p.m.	87%	6	7	746	$3{\cdot}758 \times 10^4$
b	,,	0·25 ,,	,,	90·5%	,,	13	418	$7{\cdot}075 \times 10^4$
c	,,	0·179 ,,	,,	97%	,,	5	1164	$2{\cdot}752 \times 10^5$

In one train 21 sparks can be counted, in another 8. One must not however conclude that all the sparks which occur are photographed. Some are too weak to affect the plate. The number recorded is influenced by the nature of the electrode metal, the state of the electrode surface, and the power in the spark.

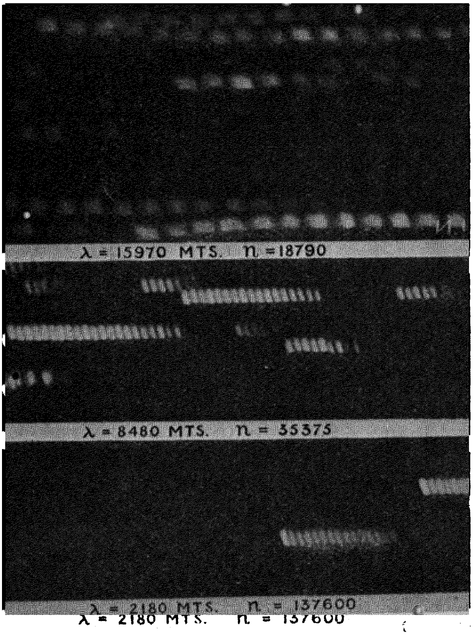


FIG. 234.—A Half-Size Reproduction of three Spark Photographs, the Oscillation Frequencies being 18,790 per sec., 35,375 per sec., and 137,600 per sec.

The Measurement of Wave-Length.—The electromagnetic field travels through space at the speed of light—that is, with a velocity of 3×10^{10} centimetres per second. If this field has a rhythmic variable character, its oscillations having a known frequency per second, and we divide the distance covered by the frequency, we get the distance travelled by one to-and-fro impulse which is called the wave-length λ, and is generally stated in metres—

$$\lambda_{\text{metres}} = \frac{3 \times 10^8}{n} = 1885 \sqrt{L_{\text{mhys.}} \times C_{\text{mfds.}}}\,.$$

Electromagnetic waves travel along thin straight wires with free ends, or along two parallel wires which are close together, at as nearly as possible the same speed as through free space, the only difference in velocity occurring at the extreme ends of the wires, where the capacity per unit of length increases and the speed in consequence is slightly less; but along all other paths, through dielectric or along inductive winding, their speed is appreciably less, and for the same frequency the wave-length is shorter than in free space to a degree which depends on the capacity, inductance, and resistance of the path.

In any oscillatory circuit, then, we convey no useful meaning by referring simply to the wave-length of the oscillation measured against the linear dimensions of that circuit, but we do convey a useful meaning if we refer to its frequency of oscillation, or to the wave-length which corresponds to this frequency in free space—that is, the wave-length with reference to a fixed standard velocity of propagation.

The simplest method to measure wave-length direct according to this standard is, to use the oscillatory circuit under test to excite stationary waves on a thin straight wire which is varied in length until it is brought into a condition of resonance; the points of maximum and minimum oscillation then provide definitely recognisable phase positions, separated by a known fraction of a wave-length which can be carefully measured.

There are many forms of circuit used for applying this principle due to Lodge, Hertz, Blondlot, and others, which are all loosely classified as "Lecher Wire" circuits. Such a circuit will be found useful for the measurement of wave-length up to about 3000 metres. For higher values it is unwieldy, and for wave-lengths of the order of 20,000 metres the size of the circuit required makes it impracticable.

But it is not possible in the majority of cases, nor is it at all convenient, to erect a calibrating circuit of this nature. Some form of portable instrument having a wide range of adjustment is required, and this necessity has produced the commercial wave-meter as we now know it.

It consists essentially of an inductance coil connected across an adjustable condenser, in combination with some form of detector which indicates when that setting of the adjustable condenser has been reached which gives resonance with the impulsing circuit under test. The wave-meter may be calibrated from a Lecher wire circuit as follows:

First, for very short wave-lengths.

Set up a horizontal thin looped wire say of No. 20 S.W.G. bare copper (ABD, Fig. 235), on a number of posts which support it on insulators, with a minimum of sag, about one metre above the ground, and in a space as free as possible from other conductors. The two parts of the loop should be parallel and near together. Make AB, for instance, 60 metres, and the distance between AB and BD 7·5 centimetres. Then excite the loop by an inductive loose coupling with the oscillating circuit CL at the point B. Bridge the loop by the neon tube N and move it backwards and forwards by the insulating handle H, to discover by means of the glow the positions of maximum and minimum potential. The loop wires should make contact preferably with tinfoil wrapped round the ends of the tube, but not touching the electrodes, the middle of the tube being left free.

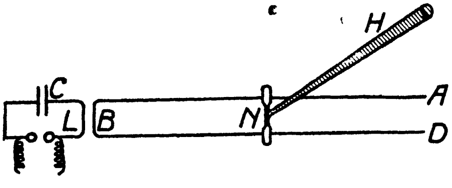


FIG. 235.—The Excitation of a "Lecher Wire" Circuit.

Adjust the circuit CL until the neon tube shows that the oscillation in the loop ABD is that of its first harmonic, maximum glow being obtained at the position AD and again at about two-thirds the length of AB at EF, Fig. 236. This will occur when the circuit CL is still a long way out of tune with the harmonic, as AD starts oscillating through impulse, and CL must be further adjusted to bring it into complete resonance, the distance the neon tube can be moved from EF towards AD before the glow disappears, steadily increasing as this condition is approached.

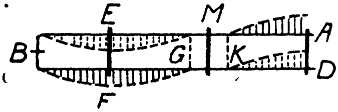


FIG. 236.—The Wire oscillating at its first Harmonic.

It is not easy to tell which is the position EF of maximum glow, but the position G at which the glow disappears when the tube is moved towards AD, and the position K where it reappears again on approaching still nearer to AD, are very distinct, so that M, the position of minimum potential, can safely be taken to be midway between G and K. The distance MB is then measured to give the half wave-length.

The calibrating circuit thus being set for a given wave-length—in the present case 80 metres—the wave-meter W, Fig. 237, is brought up to it at the position M, which is well away from the exciting circuit CL, the wave-meter condenser is adjusted to that position which gives loudest signals in the telephone—or largest ammeter deflection if such an instrument is included in the circuit—and this condenser scale position is then tabulated against the wave-length as measured from the Lecher wire ABD.

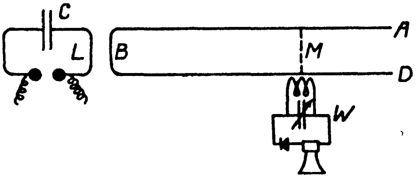


FIG. 237.—The Calibration of a Wave-Meter from a Lecher Wire.

By repeating the above operation for many different lengths of the loop wire, each time re-tuning to first the exciting circuit CL and finally the wave-meter, a sufficient number of connected values of condenser scale-reading and wave-length can be obtained for a calibration curve to be drawn for the instrument.

It should be possible with the wave-meter to detect also some of the higher harmonics in the circuit ABD, much weaker than the main oscillation but strong enough to be useful for checking the wave-meter on the very short waves, if the order of each harmonic—which must be an odd multiple 3, 5, 7, 9, etc., times the frequency of the fundamental of the circuit ABD—can be recognised.

One may place the practical limit of application of the above method, due to the spreading out of the circuit, at about 300 metres wave-length.

From 300 metres to 1500 metres the same circuit ABD with impulsing circuit CL can be used, but owing to limitation of space it may be found more convenient to excite the loop with its fundamental frequency. The harmonics will then be much stronger, and the end effect of the wires will introduce error, but the longer the wire the less the damping and therefore the sharper the tuning, and the less the proportional error due to the end effect.

Wave-length calibration from 1000 metres to 3000 metres can very well be done with small error, using the simple circuit shown in Fig. 238, which consists of two thin parallel horizontal wires of equal length supported on insulators as before, about one metre above ground and a few centimetres apart, and excited by an induction coil, sparking from one to the other plain aerial fashion. The wave-length can be taken as being four times the length of either wire measured from spark gap to free end.

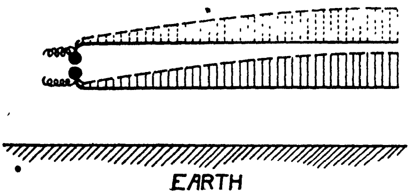


FIG. 238.—The Wire oscillating at its fundamental Frequency.

But above 1500 metres the absolute measurement of wave-length and the calibration of wave-meters can best be done by means of an inverse, or frequency method.

Thus if the oscillating circuit is connected to the spark discharger at S, Fig. 231, and we photograph the sparks in the manner already described, p. 236, and count the number per second, n, the number of complete oscillations per second will be half this value, and if we divide the figure for the speed of light by the number of oscillations per second we shall obtain the wave-length in metres, or

$$\lambda_m = \frac{6 \times 10^8}{n}.$$

The wave-lengths corresponding to the spark frequencies given in the last table are as follows:

Spark Frequency.	Wave-length.
$3{\cdot}758 \times 10^4$	15,970 metres
$7{\cdot}075 \times 10^4$	8,480 „
$2{\cdot}752 \times 10^5$	2,180 „

The greater the wave-length the easier it becomes to measure it by the spark-counting method, and values such as 40,000 metres, the longest wave-length yet used by the Marconi Company, therefore present no special difficulty.

Then for short wave-lengths the absolute calibration of wave-meters is best done by means of a Lecher wire circuit, and for long wave-lengths by inductive coupling to the oscillating circuit of a spark counter.

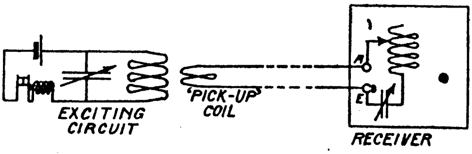


FIG. 239.—The Use of a Buzzer Oscillating Circuit for Calibration Purposes.

For general calibration work in the test room it is usual to provide one or more buzzer oscillating circuits, each comprising a set of standard inductance coils, a standard adjustable condenser, and a shunted buzzer, which can be assembled as shown in Fig. 239, for calibrating wave-meters and receivers over a wide range, each such circuit having originally been calibrated in wave-lengths by one of the absolute methods already described.

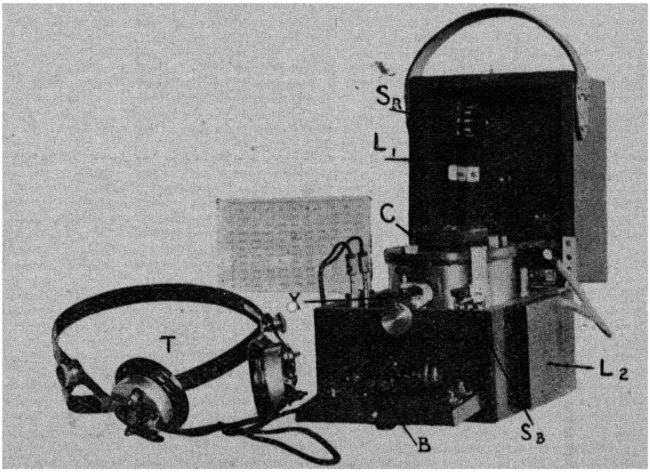


FIG. 240.—The Marconi Tuning Tester.

The Tuning Tester, shown in Fig. 240, is a calibrated adjustable oscillatory circuit, L_1L_2C, provided with a crystal detector, X, and telephone, T, so that the instrument can be used as a wave-meter, and a dry cell battery with shunted buzzer, B, so that it can be used for exciting and calibrating receiver circuits, the necessary change of connections being made by means of the switch S_B. The switch S_R alters the range.

When two oscillating circuits which separately tune to the same wave-length, λ, are coupled together, they will each tune to two wave-lengths λ_1 and λ_2, corresponding to the effective inductance values $L(I-k)$ and $L(I+k)$ of each circuit. If n, Fig. 241, is the frequency of each circuit taken separately,

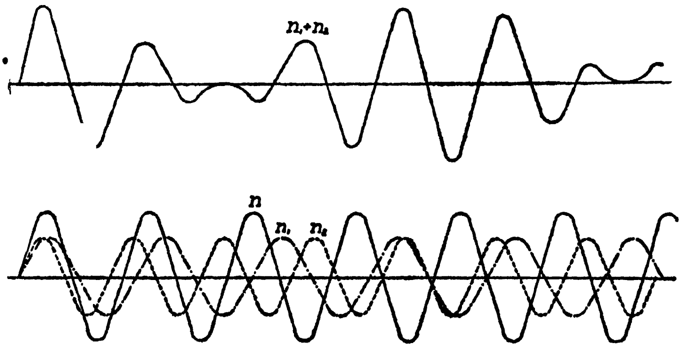


FIG. 241.—The Two Frequencies due to Tight Coupling.

and n_1 and n_2 the coupled frequencies, the resultant wave-form will have the irregular character shown by the curve n_1+n_2.

The maxima of the curve rise and fall in a periodic manner, thus superposing a "beat" frequency on the oscillation frequency. The number of beats per second—

$$B = n_1 - n_2.$$

It is obvious that the spark counter cannot differentiate between the two oscillation frequencies, but a spark will occur whenever the potential is high enough to bridge the gap.

The effect of coupling is therefore to produce irregular sparking. With tight coupling a group of sparks will pass when the amplitudes of the two waves coincide, and the number will decrease to none when the two waves are 180° out of phase.

If the photograph fails to separate the individual spark impressions of each half-oscillation discharge, it will at least indicate difference in amplitude by a difference in intensity of the spark images.

But a simple wave-meter circuit, very loosely coupled to the oscillating circuit, working by resonance, will pick out the individual wave-lengths—providing the difference between them is not too small and their damping not too great—as shown by the tuning curves, Fig. 242, the single hump curve indicating by its peak the natural wave-length of either circuit alone, the double hump curve the two wave-lengths of the coupled circuit.

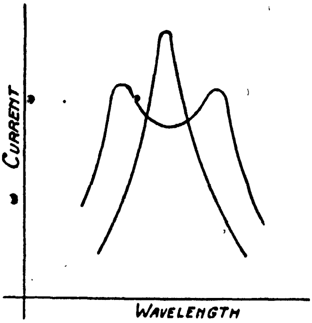


FIG. 242.—The Tight Coupling Curve obtained with a Wave-Meter.

CHAPTER XII

THE MEASUREMENT OF DIELECTRIC STRENGTH

The Factors which determine the Dielectric Strength of a material.—The Effect of Wave-Form.—High Frequency best for testing Surface, Low Frequency for testing through the Thickness.—Dielectric Hysteresis.—The Measure of Dielectric Strength.—Tests for Raw Materials.—Paints and Varnishes.—The Regulation of the Testing Potential.—Paper, Mica, etc.—The Prevention of Brush Discharge from the edge of the Testing Electrodes.—The N.P.L. Dielectric Strength test for Ebonite.—Glass Plate Testing.—Spark Voltages.—The Electrostatic Field between Electrodes of different shapes.—Tube Dielectrics.—Oil Dielectrics.—The Digby Oil Tester.—Table of Dielectric Strengths.—The Testing of Finished Apparatus.—The Duration of the "Pressure" Test.—Standard Tests.—For Generators and Motors.—For Transformers.—Windings subjected to both L.F. and H.F. Potential Strains.—The Testing of Condensers.—The most efficient form of Condenser has the Conductors embedded in the Dielectric.—The breakdown of Composite Dielectrics.—The "Rendahl" Condenser Plate.—To remove Moisture from Oil.—The Testing Voltage best obtained from a source of Power.—The Conditions of Service of a Block Condenser in a Transmitting Aerial Circuit.—An H.F. and H.T. Testing Circuit.—The Maximum Testing Voltage of the Circuit.—The Power required for H.T. Testing.—Aerial Insulators.—The 3-ft. "Flexible" Type.—The 3-ft. "Turnbull" Type.—The "Walnut" Stay Insulator.—The "Semi-Flexible" Stay Insulator.—The Stress in Insulating Bushings.—The Use of a Guard Point.—The Use of Guard Plates.—A Correctly-designed Bush Insulator.—The Effect of Corrugation on Surface Insulation.

The Measurement of Dielectric Strength.—The dielectric which separates two conductors, whether in a condenser or acting as a simple insulator, is subject to electric strain proportional to (1) the maximum potential difference between the conductors, (2) the intensity of the electric field which depends on the shape of the conductors, (3) the frequency of the rise and fall of the field, and (4) the length of time it is applied.

The dielectric may break down or disintegrate, due to the application of a momentary excessive voltage, or to a lower voltage applied for a longer time, or to a still lower voltage applied and removed, or applied first in one direction and then reversed many times per second.

Every time the dielectric receives a charge, there is a tendency towards molecular movement in it which is relieved on discharge; but if the charges succeed each other with sufficient frequency the molecular movement grows and causes heat, which, if it cannot be dissipated as quickly as it develops, encourages further molecular movement, and the disruptive strength is lowered in consequence.

The Effect of Wave-Form.—Fig. 243 shows the wave-forms of four different testing voltages which, although they each have the same maximum value, will exert very different strains on the material under test. With a constant D.C. supply (*a*), a change in molecular orientation takes place only at the moment when the charge is applied, and breakdown will be due solely to the potential. Curve (*b*) represents the rippled wave-form of a high-tension D.C. machine. In addition to the strain due to the maximum voltage there will be a periodic change in orientation of the molecules proportional to the depth of the ripple, which will tend to weaken the dielectric by the generation of heat.

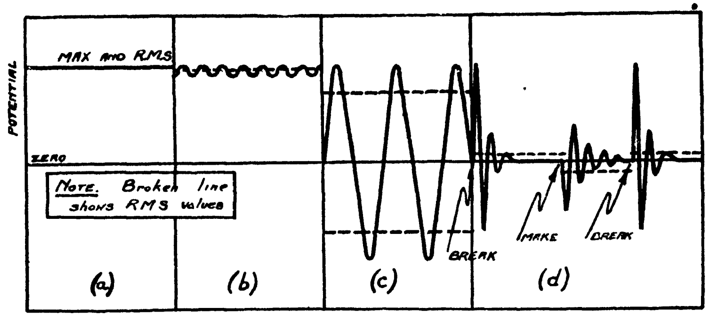


FIG. 243.—Four Types of Potential Wave-Form.

With an alternating current supply the potential wave-form has the character shown in (*c*). The loss by heat is now increased to a maximum per cycle due to a complete reversal of the charging voltage. It is clear that the total heat generated per second will be in direct relation to the frequency of the reversals per second.

Finally, (*d*) shows the potential wave-form due to an induction coil. In the first place the maximum potentials occur on the break of the circuit, and owing to the rapid fall in amplitude the maxima above zero are greater than the maxima below, so that the greatest strain will always be applied to the dielectric by a charge of the same sign. Whether the positive half of the cycle reaches the highest value or the negative, depends simply on the circuit connections. In the second place, heating occurs due to reversal of charge, but as it depends on the square of the R.M.S. value of the voltage, which is low compared with the maximum, or when compared with the R.M.S. value for a sinoidal wave-form as shown in (*c*), the weakening of the dielectric due to heating is of correspondingly less importance.

And in the third place, the small amount of energy which is available at the maximum voltage—as shown by the peakiness of the curve which indicates the short time it lasts—may be responsible either for erratic values of breakdown voltage, or for the dielectric withstanding a higher maximum voltage than it would do for a sine wave supply.

For it has been shown by P. Steinmetz and others, that before failure occurs the dielectric absorbs energy from the charging current, and disruption will only take place if there is still sufficient energy left after this absorption to bring it about. This applies particularly to the dielectric strain imposed on insulators by high-frequency currents. If the currents are only momentary the potential may reach a maximum value many times the normal disruptive voltage without the dielectric breaking down, as each individual charge lasts such a short time that it is unable to thoroughly penetrate the dielectric before it is removed and reversed. If such currents are not momentary they generate a large amount of heat, on, and just below, the surface of the dielectric, which weakens it and finally leads to puncture.

Then the best test for the *surface* of an insulator is obtained by using high frequency, and the most thorough test for the dielectric strength through the material by using low frequency.

Dielectric Hysteresis and Dielectric Strength.—The quality whereby energy is absorbed in the dielectric from the electric charge and degenerated into heat, 'is known as "dielectric hysteresis," and has the nature of a resistance.

Owing to the dependence of dielectric strength on the conditions of working as stated above, it is necessary to devise conditions of test which shall bear a close relation to those existing in practice. But as the working conditions vary so very widely, it is also useful for the purpose of standardisation to devise tests under fixed conditions, which can be applied to all dielectric and insulating material in the raw state which can be classified in the same group.

Dielectric strength is generally stated in terms of the maximum puncture voltage per millimetre or per centimetre thickness of the material. The actual thickness tested should always be stated, as the disruptive voltage per unit of thickness is higher for thin samples than for thick; and as the size and shape of the test electrodes affect the intensity of the electrostatic field applied to the dielectric, these particulars should also be given.

Tests for Raw Materials.—Spherical electrodes, which localise the breakdown puncture to the point of contact with the material, and therefore are more likely to give *average* values of dielectric strength, are much used for comparative tests; plate electrodes, which cover a larger area of the material and cause breakdown to occur at the weakest spot, are more likely to give *minimum* values of dielectric strength, and are to be preferred for working tests.

For test purposes materials naturally group according to thickness and shape, although they may vary considerably in dielectric strength.

Thus, to apply a working test to a sample paint, or varnish, or enamel, a smooth metal plate should be coated with the substance, and after being air-dried or baked, as found necessary, a puncture test can be carried out between this plate and a smooth flat electrode of, say, 2·5 cm. diameter, having rounded edges (Fig. 244).

The testing potential required may be anything from 50 to 500 volts, which can be applied most conveniently through a transformer T, Fig. 245 (*a*), the secondary winding of which is adjustable in steps, while the primary is fixed, but the volts across it can be varied gradually without jerks by using a potentiometer regulator P, for adjusting the excitation of the alternator A, instead of the more common series regulator. This is necessary, as abrupt changes of voltage start oscillation effects due to the capacity and inductance in the circuit, which add an unknown additional strain to the dielectric. A safety fuse Z should be inserted in the testing circuit.

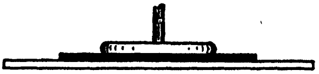


FIG. 244.—Testing a Varnish for Dielectric Strength.

The alternative circuit shown in Fig. 245 (*b*), in which a potentiometer regulator is connected direct across the A.C. mains, is sometimes used, particularly when the approximate dielectric strength is unknown and a wide range of easily variable testing voltage is therefore required. It is advantageous to earth the middle point of the testing transformer secondary winding if possible, in order to ensure that the potential on the two testing electrodes is equalised. The earthing of one electrode would cause the dielectric to break down at a lower voltage.

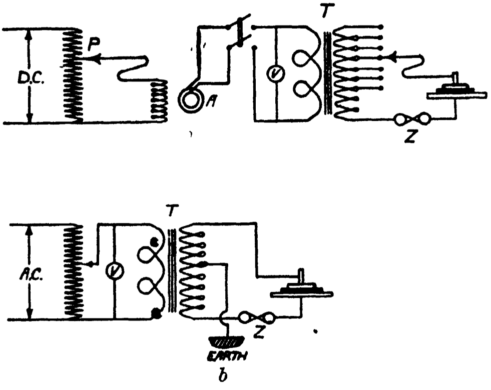


FIG. 245.—The Variable Potential Testing Circuit.

Near the point of breakdown—which can be roughly ascertained by preliminary test on another sample—the voltage should be maintained a stated time, such as one minute at each value. Then the volts V measured across the transformer primary, multiplied by the transformer ratio T_R, will give the R.M.S. fall of potential through the sample, and if a sine wave supply is being used, the maximum potential will be 1·414 times this value.

The thickness *t* of the paint or varnish can be measured by gauging the metal plate before and after painting, and the disruptive strength D can then be found in terms of the maximum volts per millimetre of thickness of the dielectric for the given frequency, or

$$D = 1{\cdot}414 \times \frac{V_{r.m.s.} \times T_R}{t_{mm.}}.$$

Paper, tape, impregnated fabrics, mica, and all sheet dielectrics of small thickness may be given a working test between smooth, flat metal plates of equal area and having rounded edges, which are set truly over each other (Fig. 246). The field of electric strain will then be parallel and very nearly uniform. Thin papers may break down at about 200 volts, impregnated papers at about 1000 volts, mica according to thickness up to several thousand volts. In this last case, particularly if the mica is thick, the air at the edges of the electrodes breaks down in the form of a brush discharge before the mica between the centres of the electrodes is punctured, and this brush, by heating the mica, tends to precipitate breakdown. Fairer and more consistent results are therefore obtained if the formation of the brush discharge is prevented by moulding wax on the test electrodes, leaving only the surface applied to the mica clean and bright, Fig. 247.

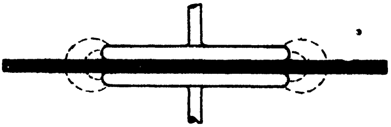


FIG. 246.—Flat Electrodes for testing Mica, Paper, etc.

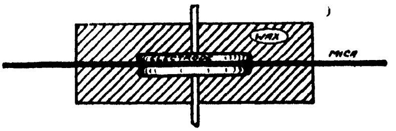


FIG. 247.—Wax Moulding to prevent Harmful Brush Discharge.

The best comparative tests are those which can be carried out between spherical electrodes on materials which have considerable thickness and which can be machined, such as sheets of $\frac{1}{4}$-inch thick ebonite, bakelite, hightensite, kalanite, stabilite, electrose, erinoid, etc.

The material under test is carefully recessed on both surfaces to the curvature of the electrodes, which are then inserted in these recesses so that the nearest points of the two metal-testing surfaces are only separated by a distance which is small compared with the radius of curvature of the electrodes. Thus 5 cm. diameter balls may be used for a testing gap of 1 mm.

This method, which is used at the National Physical Laboratory for testing ebonite, has the merit that brushing near the actual point of breakdown is avoided, the point of breakdown can be localised, the strength of the field at that point can be accurately calculated, and it is almost directly proportional to the distance between the electrodes.

There is a possibility of leakage by brushing extending from the electrodes over the edges of small samples, but this can be checked by carrying out the test under oil (Fig. 248). A small film of oil then finds its way between the electrodes and the material, but its thickness is not sufficient to affect the puncture voltage. Materials which absorb oil, such as woods, asbestos, and asbestos products, should not of course be tested under oil.

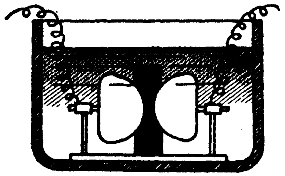


FIG. 248.—A Recessed Ebonite Plate to take Spherical Electrodes.

But if the insulating material has a grain, such as paper board, fibres, pertinax, etc., a curved recess machined in it will cause the field at the electrodes to pass partly along the grain and partly transverse to it. Such materials should not be recessed. Also it must be emphasised that the *working* test for all dielectrics should be carried out with the actual thickness used in practice, preferably with flat electrodes.

Materials which cannot be machined, or which can be machined only with difficulty, such as slate, marble, stone, earthenware, glass, and porcelain, are generally tested with flat electrodes. But sometimes the dielectric surface is irregular or has a distinct curvature. Then a tinfoil or copper gauze pad will make a suitable electrode contact.

The Marconi working test for glass condenser plates is carried out in oil, the glass being inserted between two square pads each consisting of a wooden frame W, covered with stuff S for resilience, and faced with very fine mesh copper gauze G, the gauze being carried well round the edges of the frame as shown, Fig. 249. Connection is made to the pads from a source of potential supply, and from the pads to a potential indicator, which in this case consists of a spark gap of 8 mm. between brass balls of 2 cm. diameter (Fig. 250). The top pad is balanced by a weight for easy handling, as it has often happened that 1000 plates have been tested per day.

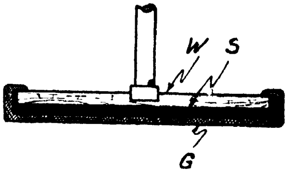


FIG. 249.—A Glass Plate Testing Pad.

Spark Voltages.—Potentials of several thousand volts are required for such tests, which are often beyond the range of any indicating instrument available.

However, a larger number of careful tests have been made by various investigators at different times to determine the breakdown voltage for different spark lengths in air between electrodes of definite shape, and it is now common practice to use these tabulated results as given below in conjunction with a suitable spark gap, for measuring extra high potentials.

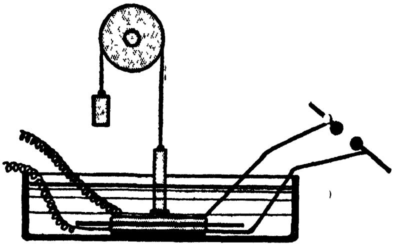


FIG. 250.—Fittings for Glass Plate Test.

To measure voltage by the spark method, two metal electrodes—which may be either needle points, a needle point and a disc, or two spheres—are mounted on an insulating stand, and provided with a micrometer screw adjustment for altering the distance between them. Having connected these electrodes to the high voltage source, the spark is started with a small gap which is gradually increased until the spark just fails to pass. Reference is then made to the table for the volts$_{\text{max.}}$ corresponding to this gap length.

Thus an 8 mm. spark in air between balls of 2 cm. diameter is equivalent to a peak voltage of 26,100 volts.

SPARKING VOLTAGES (MAX.) IN AIR AT ATMOSPHERIC PRESSURE BETWEEN VARIOUS ELECTRODES

Distance.	Needle Points.	Needle Point and Disc.	Balls 2 cm. dia.	Balls 5 cm. dia.
1 mm.	...	...	4,700	...
2 „	...	...	8,100	...
3 „	4,200	...	11,400	...
4 „	5,700	5,450	14,500	...
5 „	7,100	6,600	17,500	18,360
6 „	8,500	7,800	20,400	21,600
7 „	9,600	8,900	23,250	24,540
8 „	10,900	10,000	26,100	27,330
9 „	12,000	11,000	28,800	30,090
10 „	13,200	12,000	31,300	32,850
11 „	14,300	13,000	33,300	35,580
12 „	15,600	14,000	35,500	38,310
13 „	16,700	14,950	37,200	41,010
14 „	17,800	15,850	38,700	43,680
15 „	19,000	16,700	40,300	46,230
16 „	20,000	17,550	41,300	48,660
17 „	21,000	18,900	43,200	...
18 „	22,000	19,750	44,700	...
19 „	23,000	19,950	46,100	...
20 „	24,000	20,750	47,400	58,000
21 „	25,000	21,500	48,600	...
22 „	26,000	22,250	49,800	...
23 „	27,000	23,000	51,000	...
24 „	28,000	23,750	52,000	...
25 „	29,000	24,450	53,000	...
26 „	29,900	...	54,000	...
27 „	30,800	...	54,900	...
28 „	31,700	...	55,800	...
29 „	32,600	...	56,700	...
30 „	33,400	...	57,500	77,000
31 „	34,200	...	58,300	...
32 „	35,100	...	59,000	...
33 „	35,900	...	59,700	...
34 „	36,800	...	60,400	...
35 „	37,600	...	61,100	...
36 „	38,500	...	61,800	...
37 „	39,200	...	62,400	...
38 „	39,900	32,300	63,000	...
39 „	40,800	...	63,600	...

SPARKING VOLTAGES—*continued*

Distance.	Needle Points.	Needle Point and Disc.	Balls 2 cm. dia.	Balls 5 cm. dia.
40 mm.	41,500	...	64,200	92,000
41 „	42,300	...	64,800	...
42 „	43,000	..	65,400	...
43 „	43,700	...	66,000	...
44 „	44,500	...	66,600	...
45 „	45,300	...	67,200	...
46 „	46,000	...	67,800	...
47 „	46,800	...	68,300	...
48 „	47,500	...	68,800	...
49 „	48,200	...	69,300	...
50 „	48,900	38,000	69,800	105,000

Distance.	Needle Points.	Distance.	Needle Points.
1 inch	29,400	7 inches	112,000
2 inches	49,500	8 „	124,000
3 „	64,600	9 „	136,000
4 „	77,100	10 „	148,000
5 „	88,800	11 „	159,000
6 „	100,300	12 „	171,000

The distribution of the electrostatic field in air between electrodes of various shapes is shown in Fig. 251. Air breaks down with the lowest potential between a *point* and a *plate*, and with the highest potential between spherical surfaces of very large radius.

The spark-gap voltages given in the table are correct for un-ionised air, and for polished electrodes and new needles. If the electrodes are exposed to ultra-violet light or the unscreened light of another spark, the dielectric strength of the air is lowered. For small gaps the length of the shank of the needle electrode from point to support should be many times the length of the gap between the points.

When the spark gap is large, say 4 or 5 inches, and spherical electrodes of a radius sufficient to maintain the straight line relation between gap length and puncture voltage are not available, the point gap becomes the most general form of gauge. At such distances the differences between needle-point voltages and the breakdown voltages between thin blunted rods become negligible, and for rough tests and routine work it is usual to use $\frac{1}{4}''$ spark rods with 60° points (Fig. 252) to obviate the frequent renewals which would be necessary with needle points.

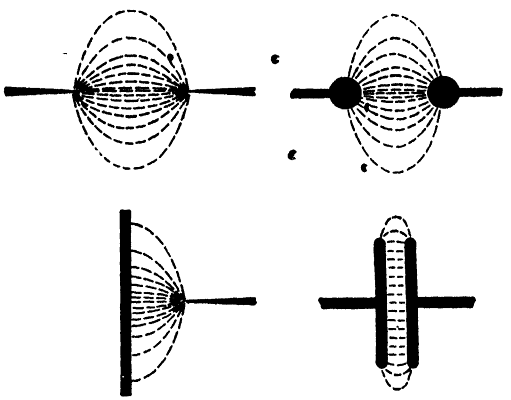


FIG. 251.—The Electrostatic Field in Air between Surfaces of various Shapes.

The spark gauge should be connected with as short leads as possible to the test electrodes, but not directly to the charging leads. This is necessary because the rate of increase of the current charging the dielectric under test is likely to be slower than the rate of increase of the current charging the smaller capacity of the test gap, and unless these currents increase at as nearly as possible the same rate, the breakdown voltage at the spark gap will not be a true measure of the puncture voltage applied to the dielectric.

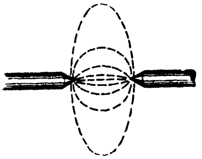


FIG. 252.—Spark Rods with 60° Points.

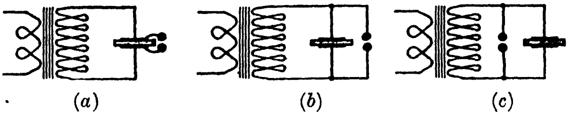


FIG. 253.—The Correct Way to use the Spark Gauge.

Thus in Fig. 253, (*a*) is the best arrangement, and (*b*) is better than (*c*).

Tube Dielectrics.—Tube dielectrics are generally fitted with two split metal cylinders, one being sprung into the inside, the other over the outside (Fig. 254 (*a*)), which cover as much of the tube as possible but not so much that sparking takes place over the ends.

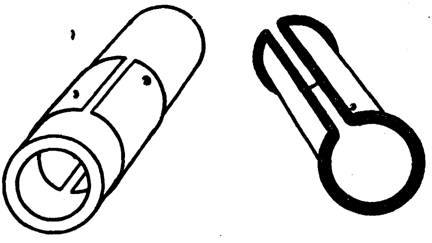


FIG. 254.—Electrodes for testing Cylinders.

While the field between the surfaces of such cylinders is fairly uniform, it is crowded at the edges, which act like a series of points, and breakdown is likely to occur near these edges in consequence. This intensified strain may be relieved by finishing off the edges of the testing cylinders with a copper gauze rope (Fig. 254 (*b*)), which gives them a curvature without robbing them of the flexibility required for making a tight spring-on contact with the tube surfaces. The field through the tube dielectric then resembles the field through a plate dielectric between flat electrodes having rounded edges.

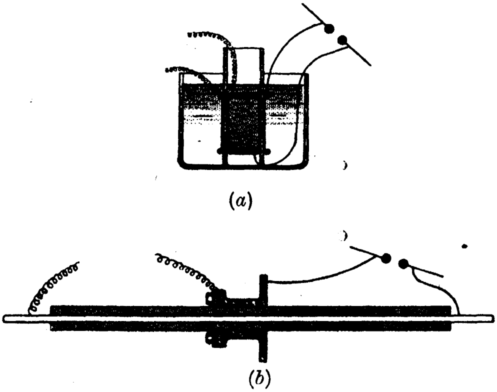


FIG. 255.—(*a*) A Tube Test under Oil; (*b*) a Case in which the Electrodes are very unequal in size.

If the tube is to be used in air, the test should be carried out if possible entirely in air; but if it has a thick wall—$\frac{1}{4}''$ for example—and if it is a material like first-grade ebonite which has a high dielectric strength, it will be necessary, in order to avoid spark-over, to leave quite a large amount of the surface uncovered by the test cylinders. Then it is usual to carry out the test with one end only in air, the other being immersed in oil, which allows the test cylinders to be brought nearer the immersed end. First one end is tested in this manner, then the other.

Fig. 255 (*a*) shows the method of connecting the spark gap to the cylinders in order that its indication of voltage applied to the dielectric may be as true as possible, the inside cylinder being connected in circuit between the supply transformer and the spark gap; and Fig. 255 (*b*) the extreme case of a leading-in insulator which has a very long central conductor, and a metal gland and earth plate half-way along its length acting as the external conductor.

Oil Dielectrics.—The dielectric strength of an oil is generally tested between electrodes which give the lowest disruptive voltage for a given gap length, that is between a point and a plate which has a large diameter compared with the oil gap.

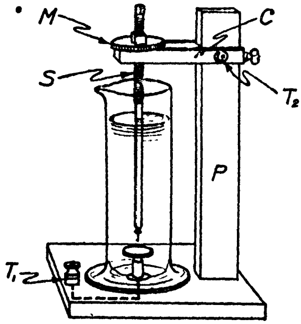


FIG. 256.—The Digby Oil Tester.

The Digby oil tester (Fig. 256) consists of a tall narrow glass jar, drilled at the bottom to take the shank of a plate electrode which passes through an oil gland into a socket in the wooden base, and this socket connects to the terminal T_1. A metal carrier C fitted with a terminal T_2 supports the stem of the needle electrode S, and can be clamped at any position on the wooden pillar P. A micrometer setting of the oil gap can be obtained by turning the milled nut M on the stem S.

To carry out a test, about 10 oz. of oil are poured into the jar, the carrier C is clamped in position, and the two terminals are connected to a dry cell and a low reading, preferably moving coil, voltmeter. The needle is fed down by means of the nut M until it just touches the disc, which will be indicated by the voltmeter, and the index of the micrometer scale is then set at zero. The oil gap is now opened a definite amount, the micrometer scale giving the true length; the voltmeter and cell are disconnected and are replaced by the high-tension supply. The voltage of the supply is then varied in the usual manner. Near the point of breakdown no brush is apparent, but the liquid becomes agitated, convective currents are set up, and finally a discharge passes, when the supply voltage and length of the oil gap are noted.

The Dielectric Strengths of Various Materials.—The dielectric strengths of a few representative materials in a uniform electrostatic field are as follows:—

Material.	Dielectric Strength.		
	Kilovolts (max.) per cm.	Volts per ·001 inch.	Comparative Values.
Air	38	100	1
Asbestos (dry)	30	...	0·8
Hornbeam	about 50	...	about 1·3
Teak	about 200	...	about 5
Red Fibre	...	200-400	2-4
Plain Paper (best quality)	...	700	7
Varnished Paper (best quality ·002″)	...	1700	17
Empire Cloth (·01″)	...	1000	10
Glass	300-600	...	8-16
Porcelain	300-600	...	8-16
Ebonite	450-900	...	12-24
Mica	...	2800-5600	28-56
Transformer Oil	75-150	...	2-4

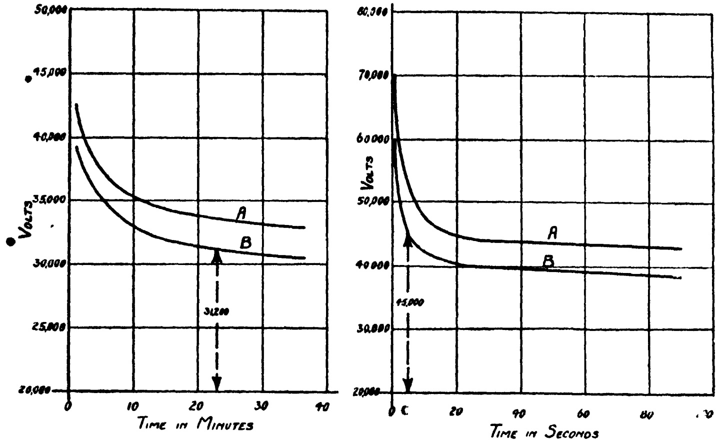
Air at atmospheric pressure breaks down on D.C. at the same voltage as it does on A.C. (max.). Solid dielectrics break down on D.C. at 1 to 1·5 times the maximum A.C. breakdown voltage for frequencies up to 500 cycles.

The Testing of Finished Apparatus.—The Duration of the "Pressure" Test.—Under certain conditions the dielectric strength of insulating materials may be permanently lowered by applying the testing voltage for too long a time.

Thus, if the energy absorbed by the dielectric from the charge accumulates in the form of heat to such an extent that the state of the solid dielectric and its properties are altered; if it softens, or becomes brittle, or chars; or if there is continuous brushing due to air breakdown on its surface, or in pockets between layers of materials having different dielectric constants, such as mica, paper, and tape, which may result in local burning, or chemical action; or, finally, if it suffers from pure fatigue, then the test has done the material permanent harm.

As a rule, solid dielectrics show very little elastic recovery from overstrain.

The curves Fig. 257 (*a*) and Fig. 257 (*b*), given by A. P. M. Fleming and R. Johnson,[1] show the time of application required for voltages of different values to break down the insulation of two types of coils A and B, tested under working conditions. A voltage of 31,200 applied for twenty-three minutes, for example, produced the same tendency to breakdown as a voltage of 45,000 applied for five seconds; and whereas the damage resulting from the five seconds test was found to be local, that resulting from the twenty-five minutes test was found to be general.



(*a*) (*b*)

FIG. 257.—The Effect of Duration of Test on Breakdown Voltage.

Then in order to cause least damage to the insulation it is considered better to recommend a high pressure applied for a short period rather than a lower pressure for a longer period.

---

[1] *Insulation and Design of Electrical Windings*, 1913.

A test duration of one minute is now standard in America and in Germany.

English practice varies considerably. The special high-grade insulation requirements of radio work are reflected in the specifications of acceptance tests for generators and transformers, which ask for pressure tests of five minutes' and of ten minutes' duration.

Generators and Motors.—To pressure test a D.C. or A.C. generator or motor, it should be assembled with all its accessories on an earth plate, to which its frame, and the casings of its regulators if iron-clad, should make good contact. All its windings, field, armature, starter and regulator should be connected in parallel at as many points as possible. The testing voltage should then be applied between the windings and the earth plate, starting at a low value and gradually increasing without jerks to the full pressure at which it is required to be maintained for the specified time. At the conclusion of the test the voltage should be lowered before breaking circuit.

The supply pressure should have approximately a sine wave form, and, if possible, the same frequency as the rated value of the machine, but up to 100 cycles there is no objection to a lower frequency being used. It should be applied after the machine has had its temperature run and is still thoroughly warmed up.

If the machine is to work in a hot climate, before pressure test its windings should be brought up to the temperature they are likely to have under running conditions in such a climate, either by passing the necessary current through them, which is to be preferred, or else by baking.

With the single exception of induction motors mentioned below, the minimum testing pressure for all machines and their parts should be 1000 volts r.m.s. Three times the terminal pressure should be used for machines rated up to 1000 volts; two and a half times the terminal pressure for machines rated between 1000 and 2000 volts; and twice the terminal pressure for machines rated at 2000 volts and upwards.

The wound rotors of A.C. induction motors have low-potential, short-circuited windings, which under working conditions are subjected to large changes of current, but no destructive potential increases. The usual pressure test is therefore five times the working voltage without any minimum limit. Thus the average working potential induced in the rotor of a 5-k.w. induction motor may be about fifty volts, and a test voltage of 250 volts applied between the winding and the core would therefore be considered sufficient.

Transformers.—The following pressure tests on transformers are carried out after they have been run on full load for a sufficient length of time for their windings to have reached a steady temperature. This may require a three to six hours' run for an air-cooled machine, and six to ten hours' run if oil-cooled.

(1) Between the low tension or primary winding and the core—which should be earthed for this test—the voltage applied being three times the terminal voltage with a minimum of 1000 volts.

(2) Between the high tension or secondary winding, and the primary winding and the core. The two ends of the secondary are joined together, and the two ends of the primary are joined together, and to the core, and to earth. Three times the secondary terminal voltage is then applied between the secondary winding and earth.

(3) Between the sections of the secondary winding, in addition to insulation between windings tested by (2). (*a*) Fifty per cent over-volts to be applied to the primary, the secondary being open-circuited; (*b*) with normal voltage applied to the primary, and the secondary open-circuited, each end of the secondary in turn to be momentarily connected, or "flashed," to earth.

The above tests, with the exception of the last, are generally applied either for five minutes or for ten minutes.

Tests of long duration are less harmful when the apparatus is immersed in oil than when it is in air and subject to the weakening effects of brushing.

Test (2) is not always enforced.

The Insulation of Windings which carry both L.F. and H.F. Currents.—Winding insulation which is subjected to, or likely to be subjected to, both low and high-frequency potential stresses, should be given endurance tests under both conditions.

As an instance, take the case of the protector chokes, X_1 and X_2 (Fig. 258 (*a*)), which are inserted in the radio transmitting circuit between the transformer secondary winding and the H.F. primary circuit. As they have to convey the L.F. charging current from the transformer to the condenser, they must be able to withstand the same L.F. maximum pressure test to earth which is given to the transformer secondary.

But, owing to their direct connection with the H.F. circuit, they are also subjected to the fluctuations of H.F. potential at the points where they join this circuit, in addition to high-frequency potentials induced in them by indirect coupling. If the chokes are connected at the discharger, D, the fluctuations of H.F. potential are least; if at the condenser C, they are greatest. The induced potentials are greatest when the coils are in resonance with the H.F. primary circuit.

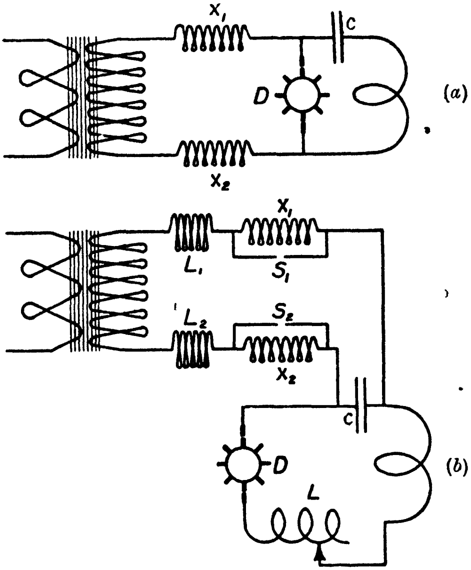


FIG. 258.—The Testing of H.F. Protector Chokes.

Then these windings should be given an effective test for dielectric strength under the most severe H.F. conditions they are likely to experience in practice, which may be carried out as follows. Insert two additional protective chokes L_1 and L_2 having greater impedance than X_1 and X_2 in the charging circuit, and nearest the transformer as shown in Fig. 258 (*b*). Connect X_1 and X_2 to the H.F. circuit at the condenser, and provide them with adjustable spark gaps S_1 and S_2. Also insert an adjustable inductance L in the H.F. primary circuit.

The transmitting set should now be sparked, using the full working potential across the transformer, and the H.F. inductance, should be varied, and the spark gaps S_1 and S_2 altered, until the value L required for resonance is found, which gives maximum spark lengths at S_1 and S_2.

S_1 and S_2 should then be opened out until no spark passes, so that the windings of the coils X_1 and X_2 can be examined to see whether injurious brushing or sparking takes place between the turns, or layers, or along the surface.

The Testing of Condensers.—It is usual to give a less rigorous test to the assembled condenser than to the individual sheets of dielectric composing it.

The reasons for this are:

(1) So as not to overstrain the dielectric by too much testing;

(2) Because there is a greater risk of surging of the charging current in a large condenser than in a small one, owing to the tendency of the current to flow to the outside sections first, and because all the sheets of dielectric in parallel have not the same capacity;

(3) The heat generated in the dielectric cannot radiate so easily from an assembly of many thin sheets as it can from a single thin sheet, so that it has more effect in weakening the dielectric.

The most efficient form of condenser is that in which the conducting plates are completely embedded in the dielectric. Such is the case with air-condensers and oil-condensers, and is closely approached by some glass-condensers which have the glass surfaces metallised by a firing process and then electroplated.

But in most condensers the dielectric is composite. Thus the mica condenser is made up of sheets of mica to which the conducting plates are fixed by a film of paraffin wax or oil, or varnish, or perhaps seccotine. Also the electric field from the edges of the conducting plates is partly in air, unless the air has been displaced by some other dielectric such as molten wax run in round the edges of the condenser.

The breakdown of the main dielectric—the mica—takes place after all the weaker dielectrics—the seccotine, varnish, oil, or wax, to name them in their order of weakness—have broken down, and have assisted by the generation of heat and chemical action in lowering the dielectric strength of the mica. It is the weakening of the material resulting from heat generated in this way which is often the sole cause of a mica condenser failing.

The dielectric strength of a mica condenser can be lowered by tight clamping, which crushes the dielectric. On the other hand a condenser made up of thin sheets of dielectric if used on A.C. must not be too loose or else it will "hum."

This is partly an effect of electrostatic forces acting over short distances between the conducting plates, and—for voltages above about 300—partly an effect of ionisation of the air imprisoned in the condenser which causes it to bombard the dielectric. Any adhesive used in the manufacture of the condenser, such as seccotine or varnish, which, as a result of the electric charge, releases gases from the water or solvent still contained in it, will be a source of weakness, as these gases being ionised will generate heat and disintegration by molecular bombardment.

The glass transmitting condenser in oil is another example of the use of a composite dielectric. At high voltages the oil film between the conducting plate and the glass lowers the strength of the condenser, but much less so than the air which it is used to displace.

The glass is the stronger dielectric and the oil therefore fails first—and, it may be noted, at a lower voltage than would be required for the same thickness tested for breakdown with the glass not present, as the higher dielectric constant of the glass increases the intensity of the electric field through the oil. The breakdown of the oil generates local heat, which lowers the dielectric strength of the glass.

But if the oil is able to circulate, fresh oil flows in to seal up each puncture as it occurs, the heat generated is carried off by convection currents, and the strength of the glass is much less affected.

In the ordinary condenser, oil can circulate fairly well outside the plates, but very little between the plates.

Condensers have been constructed, however, which use embossed or dished metal plates, as in the Rendahl design

(Fig. 259), which allows good oil circulation near the glass. The life of the condenser has thereby been prolonged, but at the expense of a reduction in capacity per glass plate, so that the question has to be decided whether the gain in dielectric strength and in efficiency per condenser is worth the loss in capacity.

A glass condenser can be weakened by too tight packing, which puts the plates under mechanical strain.

A common cause of failure is the presence of moisture, which may either be suspended in the oil, or absorbed in the glass, or may have been present on the other fittings of the condenser when it was first assembled. The suspended, or absorbed water drops, form a resistance leak at low voltage, and decompose under the influence of the charge at high voltage, causing heat and destructive brushing.

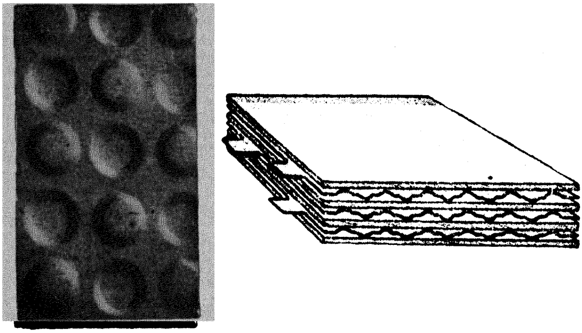


FIG. 259.—The "Rendahl" Condenser Plate.

The best way to dry oil is to bubble hot air through it, and the oil should then be heated by some other means to set free the air which it has absorbed in the process.

If the dielectric of the condenser is to receive an effective test, there must be sufficient power available behind the testing voltage to ensure that the condenser has no appreciable effect in altering the voltage wave-form. The absorption of charge by the dielectric must not have the effect of lowering the maximum voltage. Thus it would require a condenser of only a very small capacity, or absorption, to alter the induction coil wave-form shown in Fig. 243 (*d*).

A dielectric strength test of a condenser would not be complete unless it introduced conditions of strain under (1) maximum voltage, (2) surging charging current, (3) internal loss in the condenser, comparable with such conditions as they exist in practice.

If an over-voltage test is to be given to the condenser, it should be applied for only a very short time as the dielectric heat losses increase as the square of the charging current, and therefore as the square of the voltage, and no useful purpose is served by unduly weakening the dielectric as a result of such increase. A 50 per cent over-voltage test for one minute should be sufficient.

A satisfactory surging test can be made by several times abruptly interrupting the normal charging current. Every time the current is started or stopped a surge is invited, the more abrupt the stoppage the heavier the surge.

A transmitting condenser which works on an intermittent load in practice, can be given a continuous load run for five minutes at the working voltage, in order to find out whether its dielectric strength is still satisfactory when the dielectric is thoroughly warmed up.

Sometimes a condenser may be subjected to superposed potential strains which give a resultant wave-form somewhat resembling Fig. 243 (*b*). If it is possible to apply a test voltage of the same variable character as the working voltage, so much the better, but if not, the condenser should be tested to show that it can stand a steady potential equivalent to the maximum applied, plus a variable potential having an amplitude, positive and negative, of half the depth of the ripple.

A more important case is that illustrated in Fig. 260, in which the two forms of strain are imposed at different times. A block condenser C_2 is here inserted in the earth lead of an aerial circuit, to prevent the earthing of the negative main of a 1000-volt D.C. machine supplying the arc generator A. When the arc is not oscillating but is connected to the supply, C_2 is subjected to a steady pressure of 500 volts to earth. But when the arc is oscillating, as the condenser is not intended to shorten the aerial wave, and as it is inserted where the aerial current should be greatest, its capacity must be so large that on maximum aerial current—which may be 25 amperes, for example—the potential drop across it to earth falls to only a few volts. The pressure wave applied to the condenser then has the form of a small amplitude H.F. ripple, which will create heat losses in the condenser proportional roughly to the square of the depth of the ripple. In this case, then, the maximum potential strain is supplied by D.C., but the energy expended due to hysteresis is obtained from the H.F. circuit.

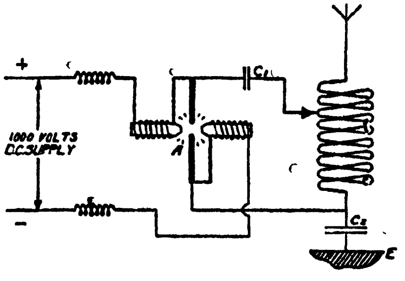


FIG. 260.—The Condensers in an Arc Circuit.

It would clearly be an unfair test to apply an A.C. pressure test at 500 volts maximum, and at such a frequency that the condenser took 25 amperes. The pressure and current, if applied from independent sources in practice, are best applied from similar independent sources during test.

The condenser C_1 presents a more simple case, as the H.F. current is responsible for both the maximum potential strain and the hysteresis loss.

The High-Tension and High-Frequency Test.—A high-frequency test is particularly effective in searching out all *surface* faults, such as cracks or foreign bodies in the glaze of a porcelain insulator.

For this purpose a circuit such as that shown in Fig. 261 may be used. The insulator X under test is one of the aerial "leading-in" type, supported at its waist by an earth plate, and having a conductor along its axis. A high-tension transformer T charges a condenser C, in the primary circuit P, of an oscillation transformer J.

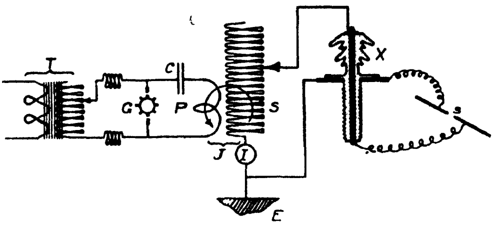


FIG. 261.—A Circuit for applying a High-Frequency, High-Tension Test to an Insulator.

When the discharge takes place at G, oscillations of high frequency are induced in the secondary circuit S, which is connected to the earth plate and centre rod of the insulator as shown.

The winding S, and the insulator X, form a circuit having inductance and capacity which requires to be tuned to the primary circuit P, in order to obtain a testing voltage having a single frequency. This is done by making the coupling between P and S very weak—either by separating the coils widely apart on the same axis, or moving their axes out of the same straight line—and then adjusting the tapping point on S until that arrangement is found which gives a maximum reading on the hot wire ammeter I, placed in the earth wire. The testing voltage applied to the insulator, as shown by the point spark gap *s*, will also then be a maximum for this degree of coupling under the given conditions of supply.

The testing voltage can be controlled over a fairly wide range by the regulation available of the power supply, such as by adjusting the field current of the alternator, or by some other method which alters the potential applied to the transformer primary, and further, by tapping off at different numbers of turns on the transformer secondary; and also by altering the coupling between the two high-frequency circuits. As the coupling is increased, and up to a certain point—the "optimum" value—the voltage applied to the insulator will increase; beyond this point currents of two distinct frequencies become detectable by wave-meter, and the amplitude of the potential applied to X, as shown by the test spark gap, then falls.

The "in-tune" voltage ratio of the oscillation transformer T is proportional inversely to the ratio of the capacities in the circuits P and S, so that any further increase of testing voltage above that given by the optimum coupling and maximum potential applied to the primary condenser C can be obtained by an increase in the capacity of C.

This will necessitate a proportional increase in the power supply if the potential applied to C is kept constant; and a decrease in the frequency of the testing current if the inductance of the primary circuit remains unaltered, which will make it necessary to increase the number of turns of S to obtain resonance.

It often happens that an induction coil is used to supply the high voltage necessary for a dielectric strength test, instead of a high-frequency supply which would be more suitable, because the testing-power available is limited, and the ratio of power input to voltage output is much higher for the induction coil *when the capacity of the insulator under test is small,* than for any form of high-frequency circuit.

The power W supplied to the condenser C is given by the formula

$$W = 2\pi n C V^2_{\text{r.m.s.}},$$

where n is the low frequency of the charging current, and therefore of the alternator. Then, to obtain high voltages at high frequency with minimum power, it is clearly of advantage to make n as small as possible. There are several other factors in practice which affect the relation between power input and testing-spark voltage, such as generator and transformer efficiencies at the various supply frequencies, loads, and power factors, and the characteristics of the spark discharger used in the primary circuit.

Some comparative test figures are given as a guide in the following tables:—

C = ·01 mfd. λ = 220 metres. Capacity of insulator X = 0·000035 mfd. Jigger coupling = 8%.

Supply.	Testing Spark at S.	Current in Insulator Circuit I.	Power Spark Gap G.	Volts (max.) at Condenser C.	Watts delivered by L.F. Transformer T.
50 ∼	2″	0·52 amp.	Rotary non-synchronous (about 700 spks. per second)	6,400	175
	4″	0·72 ,,		18,400	1,045
	6″	0·7 ,,		18,000	1,640
100 ∼	2″	0·3 amp.	Rotary synchronous	15,000	250
	4″	0·5 ,,	,, ,,	19,200	650
200 ∼	2″	0·2 amp.	Rotary synchronous	13,500	220
	4″	0·45 ,,	,, ,,	15,900	650
	6″	0·8 ,,	,, ,,	18,000	1,760
390 ∼	2″	0·1 amp.	Rotary synchronous	11,200	150
	4″	0·45 ,,	,, ,,	15,000	620
	6″	0·8 ,,	,, ,,	21,100	2,000

10″ INDUCTION COIL APPLIED DIRECT TO X.

Testing Spark at S.	Watts Input to Coil Primary.
2″	50
4″	70
6″	90

The Testing of Aerial Insulators.—The test for a porcelain "leading-in" insulator of the type shown in Fig. 261 is to first soak it in a saline solution—one handful of salt to one pail of water—for two hours, and when it has drained for five minutes, to apply a potential of 100,000 volts (max.)—equivalent to a 6″ spark between points—between the centre rod and the supporting earth plate, intermittently for two minutes, during which time the tube of the insulator must show no tendency to puncture, such as by localisation of the brushing to one particular spot, nor must there be any direct discharge from one electrode to the other over the surface.

The 3-ft. "Flexible" strain insulator (Fig. 262), which is used as a mast-head aerial support, consists of a cord core, covered with rubber and vulcanised, and then coated with a bitumastic paint so that any moisture which collects on it does not form a continuous film, but runs into drops and falls off.

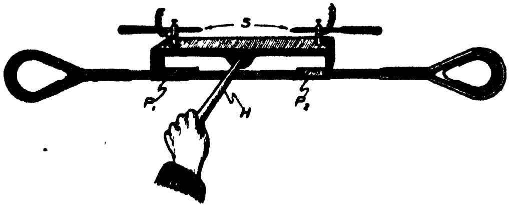


FIG. 262.—Testing a 3-ft. "Flexible" Strain Insulator.

It is tested for surface insulation by means of a high voltage supply, and the testing-handle H, which consists of an ebonite T-piece, fitted with an adjustable point-spark gap S, as a potential gauge, and two metal plates, P_1 and P_2, one connected to each spark electrode, which rest on the surface of the insulator. The 60° spark points are set 6″ apart, and the plates 7″ apart.

Having started the spark between the points, the plates are applied to the surface of the insulator and moved from one end of it to the other. During this test the spark must not leave the points for the plates, nor should the brush from the plates concentrate on any point on the surface, as this indicates an impurity or weakness in the rubber coating —particularly if the point of concentration glows red—which will sooner or later burn through.

The "wet" test of this insulator is carried out as follows. The insulator is immersed in a saline solution for one hour, it is then withdrawn, and allowed to drain for five minutes.

The testing-handle is then applied with the spark passing between the points, which are set 5″ apart, while the plates are 7″ apart as before. The plates are moved over the surface, and the spark must not take place between them in preference to passing between the points.

The 3-ft. "Turnbull" strain insulator (Fig. 263), which is also used as a mast-head aerial support, and, like the insulator just described, will stand a working load of 15 cwts.—has a core C consisting of an evenly wound hank of specially strong thread, bound with tape into a single rope, the loop of the hank at each end being left open to form an eyelet.

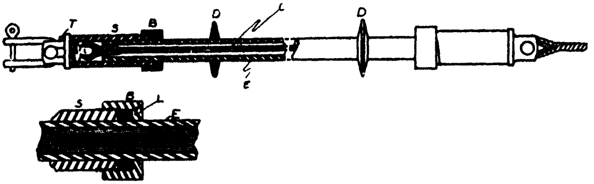


FIG. 263.—The 3-ft. "Turnbull" Strain Insulator.

This core is enclosed in an ebonite tube E, and is supported at the eyelets by the pins of the shackles T, which form the end fittings of the insulator. The whole of the space in the tube not occupied by the core is filled with vaseline, and is made perfectly watertight by means of the end sleeves S, packing-washers L, and screw-gland caps B. The two ebonite "anti-spark" discs D, which tend to reduce brushing, are also useful for reducing the mechanical shock on the tube when the insulator falls, such as when the aerial is lowered on to the ship's deck.

This insulator, dry, should stand up to a test-voltage of

148,000 volts (max.)—10″ between points—applied intermittently for one minute between the end shackles. After immersion in the standard solution for one hour, and being allowed to drain for half an hour, it should be capable of withstanding a test-voltage of 100,000 volts (max.)—6″ between points—applied intermittently between the end shackles.

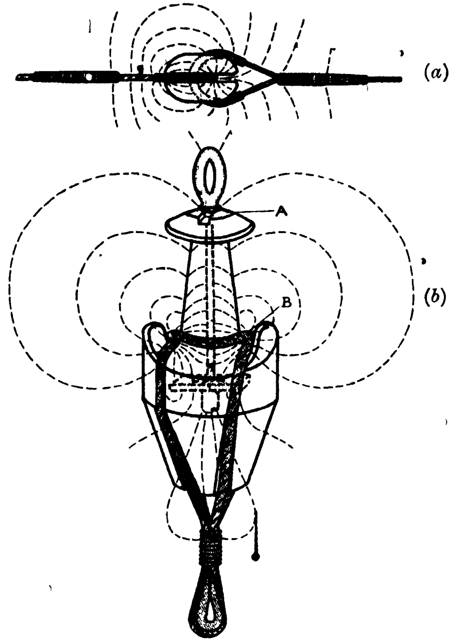


Fig. 264.—Types of Stay Insulators, showing the Electrostatic Fields between the Conductors.

A very necessary type of insulator is that used in the steel guys of masts, and towers, to reduce their power of picking up energy from the radiating aerial. They are required to stand a constant and heavy load without mechanical fracture, but in the event of breakdown occurring, the stay must still give effective support to the mast or tower. Usually, they are not required to provide effective insulation, wet, for much over 30,000 volts (max.), as the only potential strains they have to stand in practice are due to induced currents in the steel guy sections.

The "Walnut" porcelain insulator (Fig. 264 (*a*)), working load 3 tons, belongs to this class, as also does the "Semi-Flexible" porcelain strain insulator (Fig. 264 (*b*)), working load 15 cwts. In both these cases the dielectric is under compression. If breakage occurs, the guy loops in Fig. 264 (*a*) simply collapse on to each other and remain interlocked, or the steel wire strops in Fig. 264 (*b*) collapse and lock on the plate carried by the centre-bolt.

Now with these insulators, the effective insulation is that of the distance along the surface between the nearest exposed parts of the supporting conductors, A and B, as it requires a very much lower voltage to cause spark over—particularly on the "Walnut" type—than to cause electrical breakdown through the material.

Further, the spark-over voltage for a given length of surface is less than would be required to bridge a standard needle-point air gap of equal length. The reason for this is to be found in the capacity of the insulator, which in many cases acts so as to lower the dielectric strength, although not necessarily to a dangerous degree.

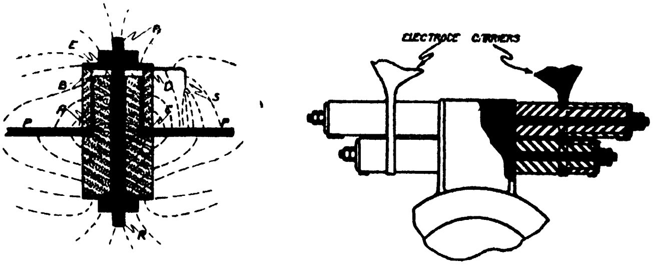
The electrostatic field between A and B (Fig. 264 (*b*)) does not follow the lay of the surface, but cuts it, and in consequence of the higher dielectric constant of the medium, the field in the material is much more concentrated than in air. In passing through the surface of the insulator there is a sharp gradient in the change from one field strength to the other, and *on* the surface the intensity is considerably greater than it would be in free air at the same voltage. As air breaks down when the field intensity reaches a certain definite value, the voltage required to produce this value will be much less on the surface of the insulator than well away from it.

Much of the loss in mast guy insulators is occasioned by brushing through the air spaces between the metal strops and the surfaces of the grooves in which they lie. If the grooves are covered with metal foil making close contact with the insulator, the capacity will be somewhat increased, but the brushing losses will be very considerably diminished.

The weakening effect of capacity in an insulator is well illustrated by the following instance:—

The Dielectric Stress in Insulating Bushings.—Fig. 265 (*a*) shows an ebonite bushed terminal fitting for a transformer, or transmitting condenser tank, a similar fitting as shown in Fig. 265 (*b*) being used for supporting the electrode carriers of the disc discharger (Fig. 43). The ebonite considerably intensifies the electrostatic field between the metal plate P and the rod R, so that in the cylindrical air space AB between the collar and the bush it is much above what it would be for the same voltage if the ebonite were not there.

The air in this space, therefore, tends to break down at a lower voltage, particularly at A, where the field is strongest, and if the terminal potential is high enough, a brush discharge takes place on the ebonite. It does not necessarily extend to B, but goes on unseen, heating, and finally burning the neighbouring surfaces of the collar and the bush, until the former flies to pieces and the latter punctures. The cure for such breakdowns is not to make the terminal bushing longer, but to increase the size of the hole in the plate so that the wall of the bushing can be made thicker; and also, if possible, to displace the film of air, which is the main cause of the trouble, by coating the bush with grease, thick oil, or other good insulating material. The outside surface of the collar along CD, being in a weaker field, is subject to much less strain than the outside surface along AB, so that if a spark point S is used to protect the bushing, which must necessarily be fitted outside CD, the gap between it and the plate should be much less than CD.



(a) (b)

FIG. 265.—The Electrostatic Field through a Terminal Bushing.

The potential difference required to flash over the surface of the collar from C to D, or the bush from A to E, is considerably less than that required to jump the same distance between points in air well away from the ebonite, due to the intensification of the electrostatic field as it cuts the air-ebonite surface. But if the terminal head is fitted with a large metal disc G (Fig. 266 (a)), which well overlaps the ebonite, there will be a considerable reduction in the number of lines of force cutting this surface, with consequent relief of surface strain and an increase in the flash-over voltage, while from the edge of the disc to the plate where the field is uninfluenced by the ebonite the breakdown potential will be practically the same as between a point and a disc.

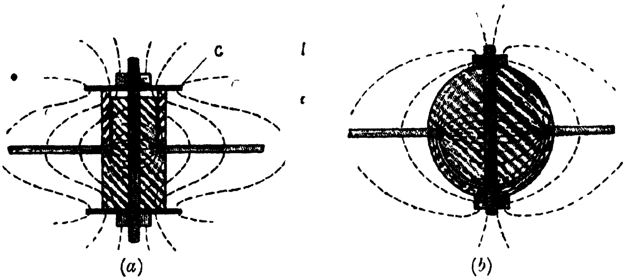

(a) (b)

FIG. 266.—(a) The Electrostatic Strain relieved by fitting Metal Plates to the Terminal Ends; (b) a correctly designed Bushing.

Fig. 266 (*b*) shows a design of insulator in which the dielectric strength would not be reduced as a result of the high specific inductive capacity of the ebonite. This is because the insulator is so shaped that the field between the two conductors either travels completely through air or completely through ebonite so that surface effects do not arise.

The Effect of Corrugation.—Frequently insulators are corrugated to increase the amount of their effective surface, and thereby their surface insulation. The best form of corrugation is that in which the surface described by joining together the bases of the conductors and of all the grooves, and the surface described by joining together the tops of the

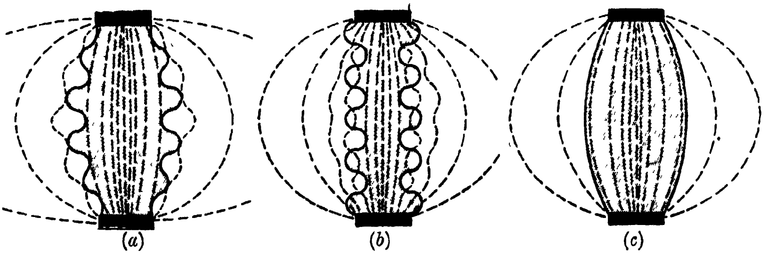

(a) (b) (c)

FIG. 267.—The Effect on the Field of corrugating the Surface of an Insulator.

corrugations, both correspond with the curvature of the field (see Fig. 267 (*a*)).

In the case illustrated in Fig. 267 (*b*) corrugation is *detrimental* to the insulator. Owing to the greater intensity of the field in the grooves, breakdown on the surface occurs much more readily than on a parallel ungrooved surface, which in its turn is not so good as one which follows the curvature of the field (see Fig. 297 (*c*)).

CHAPTER XIII

THE MEASUREMENT OF DECREMENT

The Swinging Pendulum.—Damping.—An Exponential Curve.—The Logarithmic Decrement.—The Energy which must be given to the Pendulum.—The Ballistic Galvanometer.—Method of finding the Correction for Damping.—The Case of a Simple Form of Non-Sparking Oscillatory Circuit.—The Joulean Decrement.—Spark Resistance.—Lineal Decrement.—Total Decrement of a Circuit containing a Spark.—The Decrements of Coupled Circuits.—The "Degree of Coupling."—Percentage Coupling.—When neither Circuit contains a Spark Gap.—When one or both Circuits contain a Spark Gap.—The Secondary Oscillation when the Primary Oscillation is (1) *Slightly Damped*; (2) *Strongly Damped.—Decrement Measurement from Tuning Curve.—Method of V. Bjerknes.—Method of mis-tuning until Wave-Meter Current falls to half its Value at Resonance.—The Marconi Decremeter.—Theory of Working.—The Instrument Decrement.—The Use of a Resistance for measuring the Instrument Decrement.—Decremeter for very long Wave-Lengths.—Damping in the Aerial Circuit.—To measure the Effective Resistance of the Aerial.—Earth Resistance.—Radiation Decrement.—Current Distribution in an Aerial.—Energy radiated from an Aerial.*

The Motion of a Pendulum.—When a pendulum is set swinging and is then left free to continue its motion, the amplitude of its swing gradually decreases and finally it comes to rest. Its motion has been damped by air friction. If, as in Fig. 268, a paper band moving at a constant speed in the direction of the arrow is placed beneath the swinging pendulum, so that a pencil on the bob which can move vertically in its holder just touches the paper, a periodic curve will be described as shown, each maximum of which above or below the zero line is less than the preceding one, although the time interval between them remains constant.

It will be found that the ratio of amplitude of swing in one direction to the next in the opposite direction is a constant quantity, and this is called the "damping."

Thus $$\frac{A_n}{A_{n+1}} = D, \qquad (1)$$

where n is the number of the half swing.

But the *difference* between any two succeeding amplitudes is not constant; it is a quantity which decreases in a regular manner, first quickly, then slowly, as the pendulum approaches the condition of rest, the change in magnitude being in "geometrical progression," or following an "exponential curve" (see Fig 269 (a)). If, however, instead of taking the difference of two succeeding amplitudes we take the difference of their *logarithms* (Fig. 296 (b)), we do get a constant quantity, and this difference is the logarithm of the damping, generally known as the "logarithmic decrement" or plain "decrement."

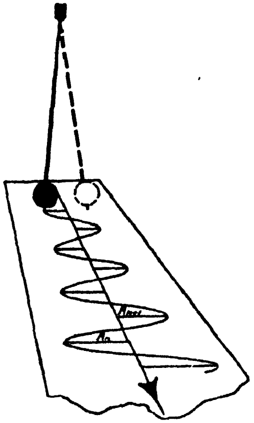


FIG. 268.—The Damping of a Pendulum.

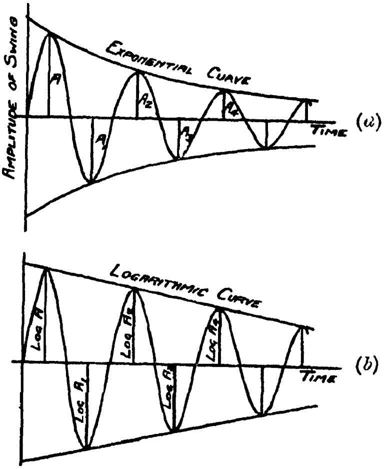


FIG. 269.—(a) An Exponential Curve of Amplitude ; (b) a Logarithmic Curve of Amplitude.

Thus $$\log_\epsilon A_n - \log A_{n+1} = \log_\epsilon \frac{A_n}{A_{n+1}} = \log_\epsilon D = d,$$

from which $$\frac{A_n}{A_{n+1}} = \epsilon^d, \quad . \quad . \quad . \quad . \qquad (2)$$

ϵ being the base of the Napierian logarithms 2·7183.

It may be more convenient sometimes to know what the damping is every complete swing, instead of every half swing; that is, from one amplitude to the next in the same direction, or for one complete period. It is clear that the decrement would then be twice what it is for one half swing or half period. Or we may require to know what it is for a quarter period, when the decrement will be half what it is for one half period. Sometimes it is the value of the decrement per unit of time which is required; then $d = b\text{T}$, where b is a constant called the "decay factor," and T is the interval of swing or periodic time for which d is measured.

It is the damping per quarter period which interests us in the case of the pendulum, as the loss of energy represented by the square of the fall in amplitude must be compensated every quarter period if the amplitude is to remain constant.

Having determined d from the measurement of two consecutive amplitudes in Fig. 268, and measured A, the amplitude of the first swing, the amplitude A_0, which the pendulum would have had if its motion had not been damped, can be found as follows:

$$\frac{\text{A}_0}{\text{A}} = \epsilon^{\frac{d}{2}}, \text{ the damping per quarter period.}$$

Then

$$\text{A}_0 = \text{A} \times \epsilon^{\frac{d}{2}};$$

and as it can be shown by the exponential theorem that

$$\epsilon^{\frac{d}{2}} = \left(1 + \frac{d}{2}\right) \text{ very nearly,}$$

$$\text{A}_0 = \text{A} \times \left(1 + 2{\cdot}303\frac{d}{2}\right), \tag{3}$$

where d is now the logarithmic decrement to the base 10 instead of the Napierian base, and therefore must be multiplied by the factor 2·303.

If W is the energy which must be given to the pendulum every quarter period to replace that lost by air friction,

$$\begin{aligned} W &= a(A_0 - A)^2 \\ &= a\left(2{\cdot}303\frac{d}{2}\right)^2, \end{aligned} \tag{4}$$

where a is some constant.

The "Throw" of a Ballistic Galvanometer.—Consider another case, that of a ballistic galvanometer, where a coil having a certain amount of inertia and constrained by a torsion spring is mounted in the field of a strong magnet.

When the momentary discharge current from a condenser passes through the coil it receives a mechanical "kick," due to the reaction of the current and the field, and the first amplitude or "throw" of the coil when suitably corrected is a measure of the discharge given by the condenser.

It is necessary to measure the damping of the coil in order to know what correction to apply.

As it swings it is subject to the damping forces of air friction, and the drag due to eddy currents which may be excited in the faces of the magnet poles and in its own metal former, forces which are very nearly proportional in magnitude to the angular velocity of the coil, and therefore to the amplitude, so that in this case also successive amplitudes plotted against time give an exponential curve (Fig. 269 (a)). First note the time of, say, 10 complete swings, by direct observation of the spot of light thrown by the coil mirror on the galvanometer scale, and set this down as the abscissa AB (Fig. 270). Suppose AB is 80 seconds, then T, the periodic time, the interval from one maximum deflection to the next at the same end of the scale, will be 8 seconds. Divide AB into twenty parts, and from each point of division draw ordinates alternatively above and below the line, on which the galvanometer deflections to right and left of the scale zero, taken each four seconds by two observers,

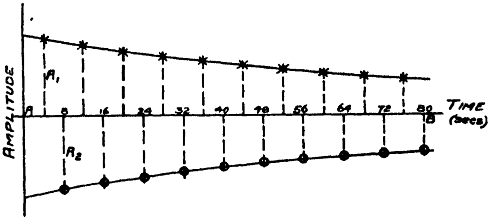


FIG. 270.—Method of finding the Amplitude of the Undamped Throw of a Ballistic Galvanometer.

can be marked. Then join up the ordinates and we have the damping curve of the instrument.

The decrement, *d*, per half period, can then be found as in the preceding case, from the ratio of one of the amplitudes to the next in the opposite direction.

Then $$\frac{A_1}{A_2} = D = \epsilon^d, \text{ and } \log \frac{A_1}{A_2} = d.$$

As we require to know what the first amplitude or quarter swing would have been without damping, we must use half this decrement to find it.

Thus $$\frac{A_0}{A_1} = \epsilon^{\frac{d}{2}},\ A_0 = A_1 \times \epsilon^{\frac{d}{2}} = A_1 \times \left(1 + 2{\cdot}303\frac{d}{2}\right). \qquad (5)$$

The Decrement of a Non-Sparking Oscillatory Circuit.—The two examples just given illustrate in a more concrete manner what occurs in any simple form of *non-sparking* oscillatory circuit which does not receive a continuous supply of energy; the electrical disturbance gradually dies out, its energy being dissipated in heat due to one or more of the following causes—conductor resistance, eddy currents, insulation leakage, and dielectric hysteresis.

It can be shown that at any moment the energy thus lost as heat due to the first two causes is directly proportional to the energy at that moment in the circuit, and the "amplitude curve" is therefore an exponential curve, and if the effect of all these causes taken together is considered, the amplitude curve is still very nearly an exponential curve.

The heat energy generated in a D.C. circuit in a time t is RI^2t, and in an oscillating circuit during one complete period T is $RI^2_{\text{r.m.s.}}T$; while the energy in the magnetic field due to the current in one complete period comprising two alternations is $2LI^2_{\text{r.m.s.}}$.

Then $$RI^2_{\text{r.m.s.}}T \propto 2LI^2_{\text{r.m.s.}}$$

The ratio of these two energies is a constant, which is the measure of the decrement per period due to heat, commonly known as the "joulean decrement" and indicated by d_j.

$$d_j = \frac{RI^2_{r.m.s.}T}{2LI^2_{r.m.s.}} = \frac{RT}{2L} = \frac{R}{2nL}, \qquad (6)$$

where n is the frequency of the circuit per second.

The logarithmic decrement of high-frequency currents is either measured per half period or per complete period, the latter being the more general practice owing to its greater utility.

In the above case R is assumed to be constant for all values of current, but if a spark gap is included in the circuit it is not so.

The Resistance and Decrement of a Spark.—The resistance of the spark using electrodes of copper, brass, or aluminium, the metals most used in practice, has an inverse and almost straight line relation with the current, and the amplitude curve in consequence is almost a straight line (Fig. 271). The spark decrement d_x therefore varies within each cycle, and from cycle to cycle, gradually increasing as the oscillation dies out. To meet this special case, in which the *difference* between two amplitudes instead of their ratio is constant, a term called the "lineal decrement" is often used, denoted by the symbol a, such that the amplitude I at a time t is given by

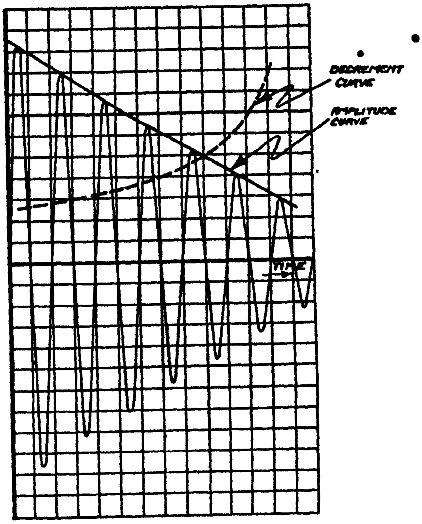


FIG. 271.—Amplitude and Decrement Curves of a Spark Current.

$$I = I_0\left(1 - \frac{a \times t}{T}\right). \qquad (7)$$

When the circuit is sparking the total decrement at any instant is—

$$d = d_j + d_x, \qquad (8)$$

and the form of the amplitude curve will depend on the relative magnitudes of these two decrements. The ohmic resistance of the circuit can be controlled, and d_j is therefore generally negligible compared with d_x.

As measurements of decrement can only be made of the *average* value during a complete train of oscillations, this value when found for a sparking circuit is not the true decrement of this circuit, which is variable, but is the decrement of a circuit having the same capacity, inductance, and energy loss, but not containing a spark gap. With this limitation understood, it can be used for most purposes of calculation, but not for plotting the true form of the amplitude curve of the sparking circuit.

The Decrements of Coupled Circuits.—When an oscillating circuit is coupled to another circuit having an oscillatory character and there is a transfer of energy between them, the decrements of the secondary circuit have also to be considered relative to the primary oscillations, as it is clear that the energy thereby consumed is no longer available for surging back again into the primary, or keeping in the combined coupled circuit.

If this secondary circuit is of the "open" type having its coupling coil connected to an aerial and to earth, its energy suffers an additional loss by direct radiation into space. The energy radiated is directly proportional to the energy in the aerial, so that if the amplitude curve were affected by the radiation decrement alone it would have an exponential character.

Now it has been pointed out, pp. 68 and 246, that the two wave-lengths which result from coupling are due to the reaction of the mutual field on the separate inducing and induced fields. If each circuit has a decrement, then the maximum strength of each field steadily falls, and in consequence the maximum strength of the mutual field also falls. If the two circuits have the same decrement, then all three fields fall at the same rate and the coupling wave-lengths will be the same as if there were no decrements. But if one circuit has a higher decrement than the other, the amplitude of the mutual field will be subject to the mean of the two decrements, and the difference between the frequencies of the coupled waves will be less than if the circuits had the same or no decrement.

The "degree of coupling," K, therefore takes decrement into account.

$$K^2 = k^2 - \left\{ \frac{d_1 - d_2}{2\pi} \right\}^2, \tag{9}$$

where k is the "coefficient of coupling" as defined on p. 221. In practice K is seldom appreciably different from k.

Then $$L_{\text{effective}} = L(1 \mp K), \tag{10}$$

and the wave-length equations will be

$$\lambda_1 = \lambda\sqrt{1 - K} \text{ for the short wave} \tag{11}$$

and $$\lambda_2 = \lambda\sqrt{1 + K} \text{ for the long wave,} \tag{12}$$

where λ is the separate circuit wave-length. If λ_1 and λ_2 can be found from the tuning curve obtained by wave-meter test, the degree of coupling is given by

$$K = \frac{\lambda_2^2 - \lambda_1^2}{\lambda_2^2 + \lambda_1^2}. \quad . \quad . \quad . \tag{13}$$

Coupling is generally expressed as a percentage of the maximum. The maximum degree of coupling is 1, which is equivalent, therefore, to 100 per cent.

Fig. 272 shows the form of the tuning curves for (*a*) weak, (*b*) medium, and (*c*) tight coupling. In this last case the short wave has almost disappeared.

The short wave oscillations in the two circuits are almost in step, but the long wave oscillations are almost 180° out of step.

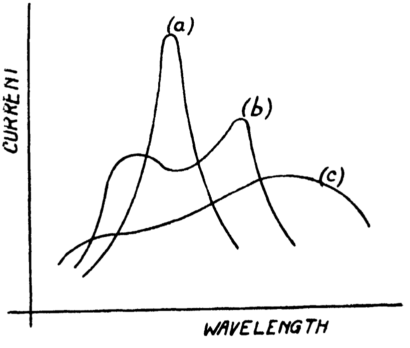


FIG. 272.—Tuning Curves for (*a*) Weak, (*b*) Medium, and (*c*) Tight Coupling.

If neither Circuit contains a Spark Gap the coupling waves divide the total decrement in direct proportion to their frequencies, and therefore in the inverse ratio to their wave-lengths; also as they have the same initial potential V_o, the initial current amplitudes are also in direct proportion to the frequencies.

Then if d_1, n_1, λ_1, and I_1 are the total decrement, frequency, wave-length, and primary or secondary current amplitude of the shorter wave in the coupled circuit, and d_2, n_2, λ_2, and I_2 the total decrement, frequency, wave-length, and primary or secondary current amplitude in the coupled circuit of the longer wave, then

$$\frac{d_1}{d_2}=\frac{n_1}{n_2}=\frac{\lambda_2}{\lambda_1}=\frac{I_1}{I_2}. \qquad . \qquad . \qquad . \qquad (14)$$

If λ is the wave-length of each circuit previous to coupling, d_P the total decrement of the primary circuit, and d_S the total decrement of the secondary circuit, then after coupling

$$d_1=\frac{d_P+d_S}{2}\times\frac{\lambda}{\lambda_1}, \qquad . \qquad . \qquad . \qquad (15)$$

and

$$d_2=\frac{d_P+d_S}{2}\times\frac{\lambda}{\lambda_2}. \qquad . \qquad . \qquad . \qquad (16)$$

Coupled Circuits which include a Spark Gap—But these relations do not hold when one or both circuits contain a spark gap. The relative decrements of the coupling waves are not then necessarily proportional to their frequencies, and it more often happens that the short wave has a lower decrement than the long wave.

The primary oscillations may die out before the secondary oscillations, in which case the double wave in the secondary circuit reverts to a single wave, and special means may be used for abruptly quenching the primary oscillations with this end in view.

Two typical cases are illustrated in Fig. 273, (*a*) showing the decrements of the oscillations in two loosely coupled circuits, there being a spark in the primary; and (*b*), the decrements of the oscillations in two tightly coupled circuits, the primary spark being so strongly damped that the primary oscillations die out after a very few swings.

The Use of a Tuning Curve for measuring Decrements.—One of the most general methods of measuring decrement is to plot a tuning curve for the circuit or circuits under test, and then to work out the decrement from its slope.

If a wave-meter circuit containing a current-measuring device is loosely coupled to an oscillating circuit with which it is not in tune, the current induced in the wave-meter will have the same periodicity as that of the energising circuit. The impulse effect of this current will start a second current in the wave-meter circuit, having a periodicity determined by the setting of the wave-meter condenser. The two currents being out of step will result in interferences which will keep the amplitude low, just as a series of ill-timed blows on a pendulum will result in swings of irregular and small amplitude. But if the two circuits are in tune, energy will be fed into the wave-meter circuit at its own periodicity and in phase with its natural oscillation, and the amplitude of the current will consequently increase until the rate at which energy is dissipated in the circuit equals the rate at which it is received. Thus at resonance there is a marked peak in the current-wave-length curve.

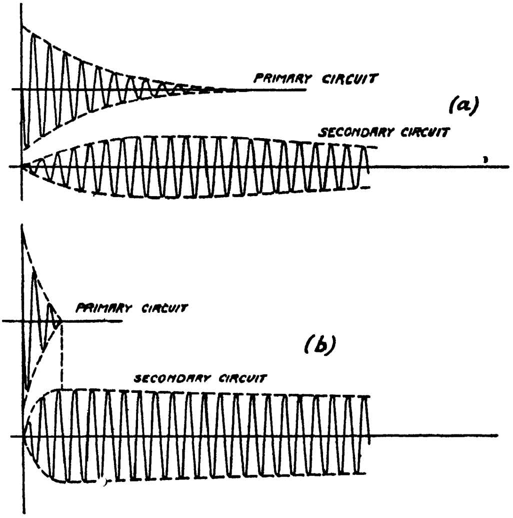


FIG. 273.—The Damping of Oscillations in Coupled Circuits; the Primary Circuit being (*a*) loosely coupled, slightly damped; (*b*) tight coupled, highly damped.

It is clear that the less the damping in the oscillating circuit the longer will the exciting oscillations continue, and the higher the resulting current in the wave-meter indicator circuit; also the less the decrement of the wave-meter circuit, the higher must the current amplitude rise before it reaches the critical maximum value at which the incoming and outgoing energies balance.

Then the current in the wave-meter circuit depends on—

(1) The coupling with the oscillating circuit, which for decrement tests should be as loose as possible, care being taken to avoid indirect coupling through neighbouring circuits;
(2) The degree of resonance between the measured and the measuring circuit;
(3) The sum of the decrements of the two circuits;

and if the best arrangement for the first two conditions is obtained and kept constant, it should be possible to establish some relation between the current in the measuring circuit and the sum of the decrements of the two circuits.

This has been done by V. Bjerknes, whose method is as follows:

First determine the exact maximum of the tuning curve. To do this draw several lines through it near the peak parallel to the axis of wave-length, such as *ac* and *df* (Fig. 274), and bisect them. When all the points of bisection such as *b* and *e* are joined, they will form a line W,*e*,*b*, which, when prolonged in a straight line through the peak to any point Y, cuts the curve at the point *h*. Then the co-ordinates of *h* fix respectively the resonance wave-length λ_R, and the instrument current at resonance, I_R.

Now select another wave-length λ_1, not more than 5 per cent less, nor 5 per cent greater than λ_R;—suppose it has exactly 4 per cent difference, the current as given on the tuning curve being I_1.

If d_1 is the decrement per period of the oscillating circuit, and d_2 the decrement per period of the wave-meter circuit, then it can be shown that

$$d_1 + d_2 = 2\pi\left(1 - \frac{\lambda_R}{\lambda_1}\right)\left(\frac{1}{\sqrt{\left(\frac{I_R}{I_1}\right)^2 - 1}}\right) \qquad (17)$$

$$= 2\pi \times \cdot 04 \times \left(\frac{1}{\sqrt{\left(\frac{I_R}{I_1}\right)^2 - 1}} \right).$$

It is usual to obtain an average value of $d_1 + d_2$, by taking the average of the squares of the current values for wave-lengths both greater than and less than the resonance wave-length, and which are an equal amount out of tune; such as I_{11} and I_{111} (Fig. 275), for wave-lengths λ_{11} and λ_{111}, respectively 4 per cent less than, and 4 per cent greater than λ_R, in which case in the above formula

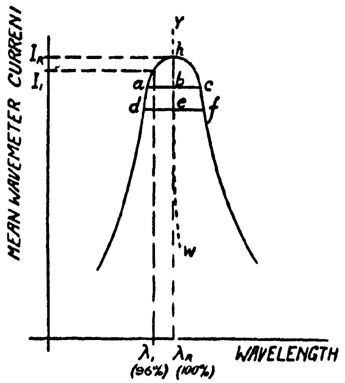


FIG. 274.—A Tuning Curve, showing the Method adopted to find the true Resonance Wave-Length.

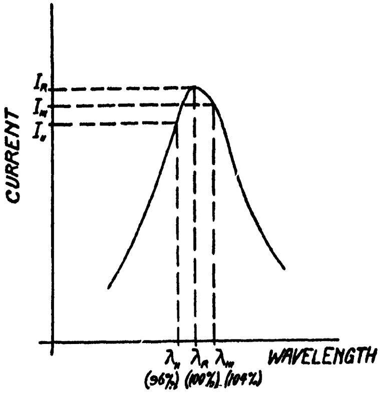


FIG. 275.—The Co-ordinates of Wave-Lengths 4 per cent less and 4 per cent greater than the Resonance Wave-Length.

$$(I_1)^2 = \frac{(I_{11})^2 + (I_{111})^2}{2}. \quad . \quad . \quad (18)$$

The formula does not apply to current values of wave-lengths more than 5 per cent out of tune.

Another method of finding the decrement $d_1 + d_2$ from the tuning curve which must also be mentioned because of its simplicity, is as follows:

First note the resonance wave-length λ_R, and the galvanometer current—or the square of the decremeter current—at resonance. Next note the wave-lengths λ_1 and λ_2, respectively greater than and less than λ_R, at which the galvanometer current—or the square of the decremeter current—falls to half the resonance value; then the last term in equation (17) becomes unity, and it can be shown that

$$d_1 + d_2 = \pi\frac{\lambda_1 - \lambda_2}{\lambda_R}. \qquad (19)$$

Here again for the equation to be true, λ_1 and λ_2 must not differ from λ_R by more than 5 per cent.

Marconi Decremeters.—It is essential for the accurate measurement of decrements by these methods that the mean current in the oscillatory circuit should remain constant while the "in-tune" and "out-of-tune" wave-meter mean current measurements are being taken. If, as is usually the case, this cannot be ensured for any length of time, then the next best thing is to speed up the taking of the measurements.

This is provided for in the Marconi Decremeter, which is simply a wave-meter so constructed that the natural period of its circuit, as set at any value within the range of the adjustable condenser, can, by means of push-button switches, be instantly increased or decreased a fixed amount—4 per cent. The resonance current, and the 4 per cent out-of-tune current, as shown by a pointer galvanometer, are noted, and their ratio is referred to a table in the lid for the equivalent decrement.

Fig. 276 is a simplified diagram of the instrument. L_1 is the main inductance coil wherewith it is loosely coupled to the oscillating circuit; C is the adjustable tuning condenser; H the non-inductive heater of the thermo-couple E, which is in circuit with the galvanometer G, the three parts forming the combination used for measuring the decremeter mean current; L_2 and L_3, inductance coils of equal value, for throwing the circuit 4 per cent out of tune either below or above the

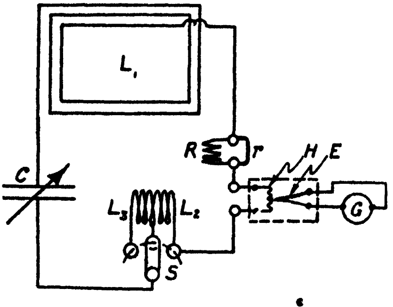


FIG. 276.—A Simplified Diagram of the Marconi Decremeter.

resonance wave-length by means of the switch S; and R, a non-inductive resistance coil which is introduced in the circuit by removing the short-circuiting piece r when it is required to measure the decrement of the instrument.

It is clear that if the change of wave-length is obtained by altering the inductance, the expression

$$\left(1-\frac{\lambda_R}{\lambda_1}\right) \text{ becomes } \left(1-\sqrt{\frac{L_R}{L_1}}\right),$$

and this is worked out as a constant for each instrument, which we shall call P. Also, as the heat developed in the thermo-couple heater is proportional to I_2R, and the E.M.F. generated in the thermo couple itself is proportional to, the temperature of the junction due to this quantity of heat, the current reading of the galvanometer, I_G, is proportional to the *square* of the mean decrement current.

Then in place of the expression

$$\frac{1}{\sqrt{\left(\frac{I_R}{I_1}\right)^2-1}} \text{ we may write } \frac{1}{\sqrt{\frac{I_{GR}}{I_{GI}}-1}},$$

and thus

$$d_1+d_2=2\pi P\frac{1}{\sqrt{\frac{I_{GR}}{I_{GI}}-1}}, \quad . \quad . \quad (20)$$

A table connecting (d_1+d_2) and $\left(\frac{I_{GR}}{I_{GI}}\right)$ is provided with the instrument.

We have next to separate the decrement of the instrument from that of the oscillating circuit. In order to do this, a non-inductance resistance, R, is added to the decremeter circuit by withdrawing the short-circuiting piece r, which alters the decrement of the instrument from d_2 to d_2+d_3. The total decrement is then measured as before, when

$$d_1+d_2+d_3=2\pi P\frac{1}{\sqrt{\frac{I_{2GR}}{I_{2GI}}-1}}, \quad . \quad (21)$$

then $$d_3 = (d_1 + d_2 + d_3) - (d_1 + d_2). \qquad (22)$$

Now it can be shown from Bjerknes' equations that if the coupling between the two circuits is very weak, and they are quite in tune, then the instrument mean current squared

$$I_R^2 = I_{GR} = Z \times \frac{1}{d_1 d_2 (d_1 + d_2)}, \qquad (23)$$

where Z is a factor involving the self and mutual induction of the circuits, and the mean potential of the oscillating circuit.

If we alter the instrument decrement from d_2 to $d_2 + d_3$ by adding a resistance which is non-inductive so that the inductance values in Z are not affected, and the decrement of the primary circuit owing to the weak coupling also remains unaffected, we get a new value of instrument mean current squared, and $(d_2 + d_3)$ must be substituted for d_2 in the current equation thus:

$$I_{2R}^2 = I_{2GR} = Z \times \frac{1}{d_1 (d_2 + d_3)\,(d_1 + d_2 + d_3)}. \qquad (24)$$

From (23) and (24) it follows that—

$$d_2 = d_3 \times \frac{1}{\frac{I_{GR}}{I_{2GR}}\left(\frac{d_1 + d_2}{d_1 + d_2 + d_3}\right) - 1}, \qquad (25)$$

and by subtracting this value from the value found by (20) we get the decrement of the oscillating circuit alone, d_1.

The resistance R is wound with fine wire. Its value, therefore, does not vary with the frequency, and is given with the other constants of the instrument. The decrement due to it can be calculated from (6):

$$d_3 = \frac{R}{2nL} = \frac{R_{\text{ohms}}}{600 L_{\text{mhys.}}} \times \lambda_{\text{metres}} = U \times \lambda_{\text{metres.}} \qquad (26)$$

Thus U is a constant for each instrument, which must be multiplied by the wave-length in metres to get d_3. This calculation provides a check on the value of d_3 obtained by the process described above, which must be carried through in order that some value of I^2_{2R} or I_{2GR} may be obtained for use in the other equations.

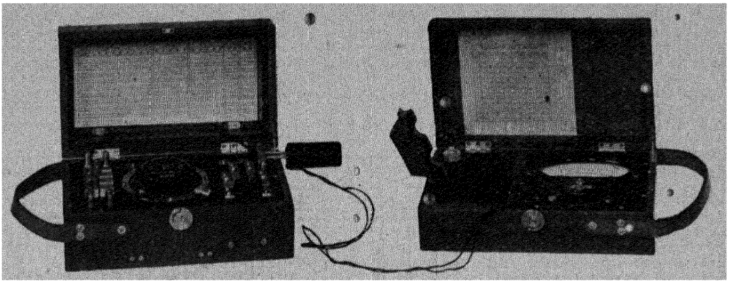


FIG. 277.—A View of the Marconi Decremeter.

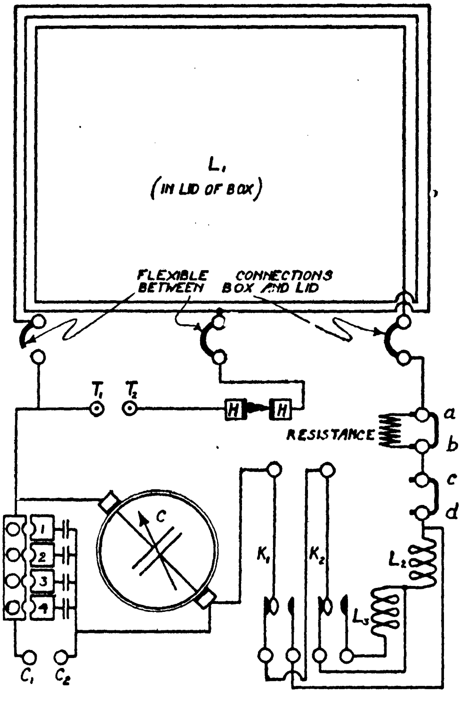


FIG. 278.—Circuit Diagram of Decremeter with Range 1300 Metres to 9500 Metres.

A view of the instrument with its galvanometer box and thermo element fitted is shown in Fig. 277, and its working diagram in Fig. 278. Its range is from 1300 metres to 9500 metres.

L_1 is the main inductance on a former in the lid, so placed for convenience of "picking-up" from the oscillating circuit. The condenser consists of a part which is continuously variable, C, and another part which is variable in steps by plug connections, 1, 2, 3, 4. The keys K_1 and K_2 are represented in Fig. 276 by the switch S. Their normal position when the resonance adjustment by condenser is being obtained is as shown. Pressing K_1 decreases the wave-length 4 per cent by removing L_2; pressing K_2 increases the wave-length 4 per cent by inserting L_3.

For simple wave-length measurements, a carborundum crystal in the clip HH, with telephone in the sockets T_1T_2, is used as a detector; connection being made across only a small part of L_1 in order to disturb the circuit as little as possible.

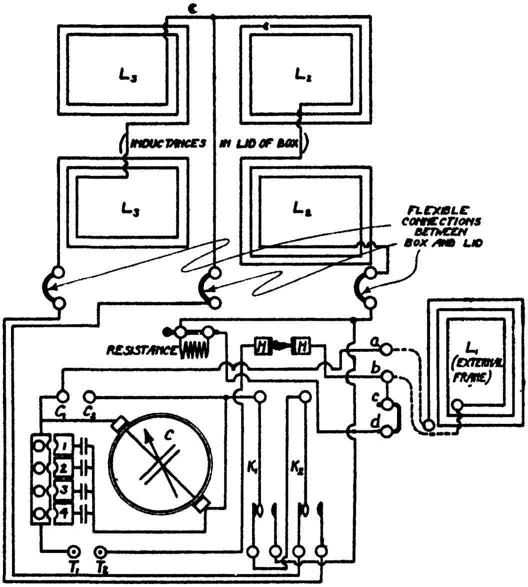

L3
L2
INDUCTANCES IN LID OF BOX
L3
L2
FLEXIBLE CONNECTIONS BETWEEN BOX AND LID
RESISTANCE
H
H
a
b
c
d
L1 (EXTERNAL FRAME)
C1
C2
C
1
2
3
4
K1
K2
T1
T2

FIG. 279.—Circuit Diagram of Decremeter with Range 5000 Metres to 30,000 Metres.

The terminals C_1, C_2 are for the measurement of external condenser capacities less than the maximum capacity of the decremeter condenser with which the condenser under test is placed in parallel. Larger capacities can be measured if the condenser is inserted at *c*, *d*, the short-circuiting piece being removed, thus placing it in series in the circuit. For particulars of these methods refer to p. 208.

The self-induction of a coil can also be measured if it is inserted at *c*, *d*, see p. 218, care being taken to avoid any mutual effect between the coil under test and the coils of the instrument.

The terminals *c*, *d* are used for the thermo-couple connections when tuning curves are to be plotted, or decrements are to be found from galvanometer readings, the short-circuiting piece, *a*, *b*, being removed to insert the resistance R, when testing out the instrument decrement as already described.

If a suitable ammeter—or any form of current-measuring device—were to be inserted direct in the circuit in place of the thermo couple, the decrements would be obtained from the ratio of the square of its readings as shown in (17).

The circuit diagram of a decremeter suitable for working on very long wave-lengths—from 5000 metres to 30,000 metres—is shown in Fig. 279.

The value of the main inductance L_1—the picking-up coil—is about 6400 micro-henrys. It is wound on a square former and is separate from the instrument to which it is attached by twin flexible leads. The mis-tuning coils L_2 and L_3, which change the wave-length 4 per cent either way, are mounted in the lid of the box. They are each split in two and arranged astatically, so as to neutralise their pick-up effects.

The circuit otherwise resembles that shown in Fig. 278.

The Damping in the Aerial Circuit.—Energy is lost from the aerial circuit and dissipated in heat by—

(1) The resistance of the aerial conductors.

(2) The effective resistance of the "earth," including the contact resistance at the earth-plate.

(3) "Brushing" on the conductors and brush leakage at insulating supports.

(4) Dielectric hysteresis in the case of any condenser connected directly in the circuit, or indirectly subject to charge and discharge by the aerial current, such as a supporting insulator having a measurable capacity as a condenser.

(5) The currents induced by the aerial current in neighbouring conductors, such as the steel mast and steel guys.

Finally, there is the energy lost from the aerial by electromagnetic radiation.

The combined action of all these causes creates a damping in the aerial circuit which follows very nearly an exponential law, just as if it were due entirely to a resistance. The "effective resistance" of the aerial circuit is that value of non-inductive resistance which, when placed in series in a closed circuit containing both capacity and inductance equal to that of the aerial, gives the same damping.

The total decrement d_a, therefore, has a logarithmic character and can be found by one of the methods already described.

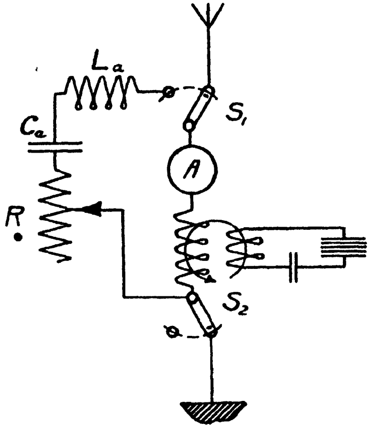


FIG. 280.—The Aerial "Effective Resistance" Test.

Either a "quenched spark"—that is, one which ceases after the first few oscillations—should be used in the aerial exciting circuit, so that the induced oscillations can continue subject to the decrement of the aerial circuit alone, and the total decrement measured, only has then to be corrected for the decrement of the instrument; or, alternatively, a source of continuous waves, which is to be preferred.

The total decrement can be calculated if the "effective resistance" of the aerial can be measured, by using the formula—

$$d_a = \frac{R_a}{2nL_a} = \pi R_a \sqrt{\frac{C_a}{L_a}} \quad . \quad . \quad (27)$$

First measure the effective inductance L_a of the aerial as described on p. 219, also the effective capacity C_a as described on p. 209. Then arrange an inductance coil and condenser having such values, in series with a non-inductive resistance R, and switches S_1 and S_2 (Fig. 280) as a change-over circuit for the jigger secondary and aerial ammeter. With aerial and earth connected and using either highly damped—quenched spark—or undamped oscillations in the exciting circuit, note the aerial amperes. Next change over to the test circuit and adjust R to the value R_0 which gives the same reading on the ammeter. Then R_0 is the effective resistance of the aerial.

Another method, which requires a source of undamped oscillations for exciting the aerial circuit, is as follows:

First measure the aerial current I due to resonance with the primary exciting circuit. Next insert a known resistance R_1 which reduces the aerial current to I_1—

Then
$$R_a = \frac{R_1}{\frac{I}{I_1} - 1}. \qquad . \qquad . \qquad . \qquad (28)$$

It is very difficult, if not impossible, to separate all the decrements in the aerial circuit. In a few favourable cases the resistance of the aerial conductors can be calculated. Also if the resistivity r of the ground can be measured —a divided earth, as suggested by J. A. Fleming, will allow the resistance to be measured between the two parts from which the soil resistance per cubic centimetre can be obtained —and if the capacity of the earth conductors C_e considered simply as a free space capacity area can be calculated—the value depends considerably on the form of the aerial of which it is a part—then the resistance of the earth system can be worked out from the formula—

$$R_e = \frac{r}{4\pi C_e}. \qquad . \qquad . \qquad . \qquad (29)$$

What really is essential, however, is to measure the total decrement d_a, and measure or calculate the radiation decrement d_ϵ, as the difference between these two values gives the sum of all the true losses, represented by the term d_e, which is nominally the earth decrement.

Then
$$d_a = d_\epsilon + d_e. \qquad . \qquad . \qquad . \qquad (30)$$

and the efficiency of an aerial will be given by

$$e = \frac{d_\epsilon}{d_a}. \qquad . \qquad . \qquad . \qquad (31)$$

The Radiation Decrement.—The energy radiated from an aerial can be expressed in the form

$$W = R_e I^2_{\text{r.m.s.}} \quad . \quad . \quad . \quad (32)$$

where $I_{\text{r.m.s.}}$ is the current indicated by an instrument inserted in the aerial near the earthed end. This is similar in form to the expression for the energy dissipated in heat by resistance, and the factor R_e is therefore called the "radiation resistance." Now R_e is a composite factor involving the radiating qualities of an aerial as defined by its height h and natural wave-length λ, and also a correcting factor a for the distribution of current through the aerial as determined by its shape.

For in an aerial which is free at one end and earthed at the other the distribution of current is not uniform, and therefore the radiation cannot be uniform. The current amplitude is greatest at the earthed end but it falls gradually to nothing at the free end, and the rate of fall differs with the form of the aerial circuit.

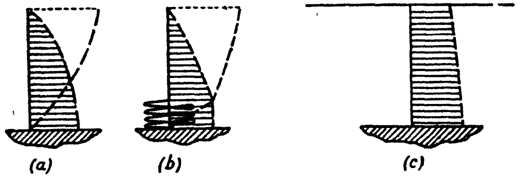


FIG. 281.—The Distribution of Current in (*a*) a Simple Aerial; (*b*) an Aerial loaded with a large Inductance Coil; (*c*) the Vertical Part of an Umbrella Aerial.

Thus in Fig. 281, (*a*) shows the sinoidal current distribution in a simple earthed aerial; (*b*) the almost straight line current fall along an aerial having a large inductance at the earthed end; and (*c*) the almost even distribution of current along the vertical part of an earthed umbrella aerial.

Then to calculate the energy radiated from the whole of the aerial we must obtain a value for the average current, which obviously will be different from the r.m.s. current measured at the foot of the aerial, and also will be different for the three cases mentioned when the r.m.s. current measurements at the foot of the aerial are identical.

In (*a*) the average current will be $\frac{\pi}{2}$ the instrument current.

In (*b*) the average current will be $\frac{1}{2}$ the instrument current.

In (*c*) the average current will be practically the same as the instrument current.

Then $$W = R_e \, I^2_{\text{r.m.s.}} = 1{,}580 a^2 \left(\frac{h}{\lambda}\right)^2 I^2_{\text{r.m.s.}},$$

and $$R_e = 1{,}580 a^2 \left(\frac{h}{\lambda}\right)^2. \tag{33}$$

For a simple earthed aerial such as

$$(a)\ R_e = 640 \left(\frac{h}{\lambda}\right)^2 \text{ ohms.}$$

For an earthed aerial with large inductance—

$$(b)\ R_e = 395 \left(\frac{h}{\lambda}\right)^2 \text{ ohms.}$$

For an earthed umbrella aerial—

$$(c)\ R_e = 1{,}580 \left(\frac{h}{\lambda}\right)^2 \text{ ohms,}$$

and $$d_e = R_e \sqrt{\frac{C_a}{L_a}}. \tag{34}$$

CHAPTER XIV

THE MEASUREMENT OF THE DIRECTION, AND THE DISTANCE OF TRANSMITTING STATIONS, AND THE INTENSITY OF RECEIVED SIGNALS.

The Directional Effect of certain Aerials.—The Marconi-Bellini-Tosi Method of Direction Finding.—As Applied to Ship Stations.—The Working Theory.—The Practical Operation of the D.F. Set.—Causes of Error.—The Distance of the Transmitting Station.—D.F. Land Sets.—D.F. Set with Rotary Frame Aerial.—The Measurement of Audibility.—Definitions of Audio Current, Audibility, and Audibility Current.—The Resistance and Reactance of the Telephone.—Comparative Audibilities.—The Relation between the Aerial Current Received and the Audio Current,—for both Spark and C.W. Signals.

The Directional Effect of certain Aerials.—An aerial free at both ends, which has a horizontal length many times its height, shows directional effects, signals being received strongest in the direction of its length and weakest at right angles thereto.

If the aerial is earthed at one end, strongest signals will be received from the direction opposite to that in which the free end is pointing.

An unearthed triangular aerial having a long base line compared with its height is similar in its behaviour to a free horizontal wire, but is somewhat less directional and has a greater receiving range.

If (A) Fig. 282 represents the receiving station, then the polar diagrams give the relative strengths of signals received from the different points of the compass for the three types shown.

The Marconi-Bellini-Tosi Method of Direction Finding, which has received the widest application both on sea and on land, and which in the hands of a capable operator can often give direction within a degree, and sometimes within half a degree, on board ship makes use of an aerial system which consists essentially of two identical loops of wire, insulated from each other and also from earth, and erected in vertical planes which are truly at right angles to each other.

The loops ordinarily take, the form of triangles (see Fig. 283), suspended at their apexes by means of a special egg-shaped insulator from a triatic or other fore-and-aft stay, or from a sprit, gaff, or bracket, on one of the masts. They should, as far as possible, be erected so that there are no metallic masses nearer to one than the other, and the ordinary aerial of the ship, shown dotted, must be symmetrically placed with respect to them.

Their horizontal base wires cross the ship at an angle of 45° on either side of its centre line, the two bottom corners of each triangle being usually made fast to insulators attached to stanchions on the ship's side.

The base wires should not be less than 30 ft., and the wires running to the triatic less than 40 ft. each in length. The base wires are split by insulators at their point of intersection, and the four free ends enter the receiving cabin through four partition insulators, and connect to an instrument called a Radiogoniometer, D (Fig. 283). The range of the installation suffers to some extent if these end connections are very long.

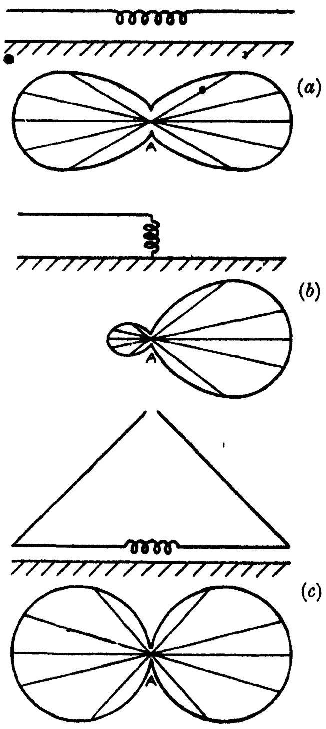


FIG. 282.—The Directional Effect of (a) an Insulated Horizontal Aerial; (b) a Marconi Bent Aerial; (c) a Bellini-Tosi Triangular Aerial.

Each aerial circuit, as shown in Fig. 284, is completed in the radiogoniometer through a very carefully wound coil, which is split at the exact centre and connected to an adjustable air condenser.

The two goniometer coils are wound with open turns, and are mounted concentrically and at right angles to one another so that there is no mutual inductance between them. Where the two axes cross is made the centre of a third coil (X, Fig. 284) wound on a spherical former, and mounted on a vertical spindle fitted with a handle so that it can be turned for exploring purposes, and which is connected externally to the receiver (R, Fig. 283).

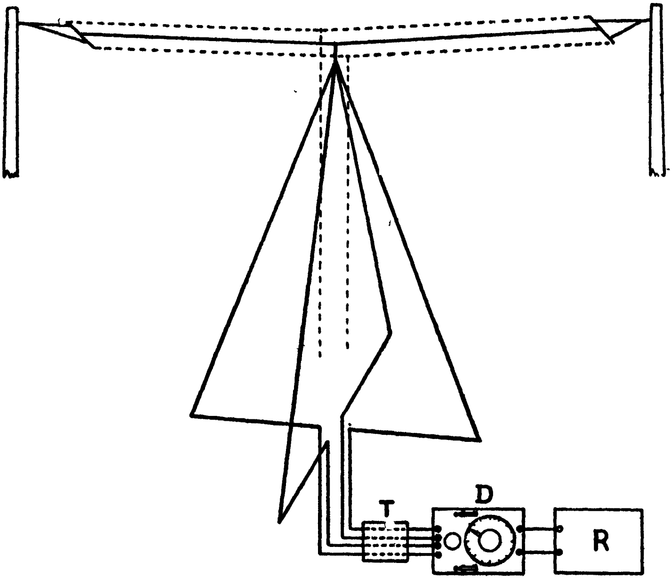


FIG. 283.—The General Arrangement of a D.F. Set on Board Ship.

The coupling between each goniometer coil and the exploring coil under similar conditions must be the same.

A pointer, carried on the spindle, moves over a scale divided into angular degrees, and measures the angle of the setting of the exploring coil.

The receiver may be any one of the standard types in general use, but what would otherwise be its aerial circuit should preferably consist—as shown in Fig. 285—of an adjustable condenser completing one oscillatory circuit through the goniometer exploring coil, and another through a coupling coil of equal inductance in the receiver, so that the condenser provides a simultaneous adjustment for the two circuits.

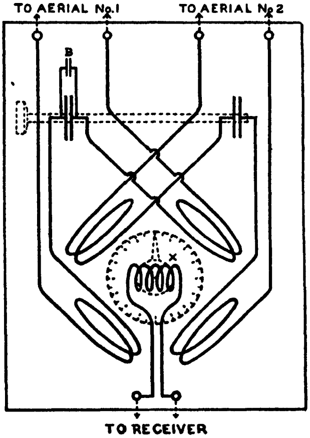


FIG. 284.—The Ship Type Radio-goniometer Circuit.

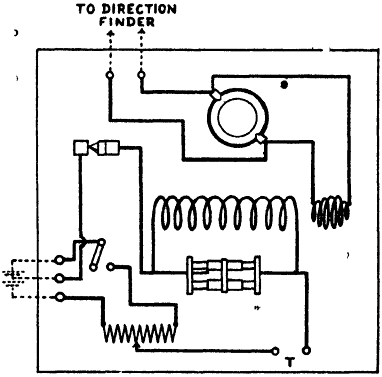


FIG. 285.—A Simple D.F. Receiver Circuit.

The Direction Finder—or "D.F." Set, as it is generally called—also includes a Tuning Tester, an instrument which consists of a calibrated adjustable oscillatory circuit excited by a buzzer (see Fig. 286) which is used for the local excitation of the two aerials from a source having the same wave-length as that of the expected signals, when this is known, and when it comes within the range of the tester. This enables the aerial circuits to be tuned to the correct wave-length beforehand, so that when the signals are received, the operator can apply himself immediately to the determination of their direction.

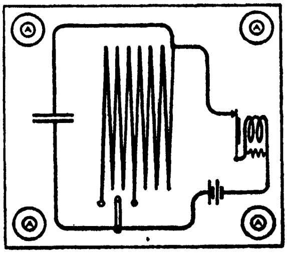


FIG. 286.—The D.F. Tuning Tester.

The position of the tester is between the aerials and the goniometer, T (Fig. 283), the four aerial connecting leads passing through insulated channels in the tester box, A (Fig. 286). This ensures that the signal currents induced by it are of equal intensity in the two aerials. The tester must be installed as far from the receiver as possible to prevent direct action, and should also be about three feet from the goniometer.

The Working Theory. — Each aerial loop receives best when its plane is in the direction of the sending station; at right angles thereto, the aerial will receive nothing. In intermediate positions the strength of the induced signal currents varies as the cosine of the angle between the aerial loop and the direction of the sending station. Except in the two cases just mentioned, signal currents are induced in both aerials, and—providing the aerial circuits are absolutely identical—their relative intensities depend on the direction of the sending station with reference to the planes of the two aerial loops.

These currents pass through the corresponding crossed coils in the goniometer, and produce in the space enclosed by them two magnetic fields at right angles to each other, having relative strengths proportional to the currents creating them, which combine to form a resultant field at right angles to the direction from which signals are coming.

The exploring coil will consequently receive the strongest signals when its plane is at right angles to that of the resultant field, and—if the crossed coils are in the same planes as the crossed aerials—when its plane is in the direction of the incoming signals. Then the pointer which indicates the position of the exploring coil consequently shows the direction of the sending station.

However, as the goniometer is provided with a fixed scale and pointer it is not necessary to align it with the two aerials, for the position of the exploring coil relative to the fixed coils as shown on the scale will be the same as the direction of the incoming signals relative to the planes of the two aerials. The instrument can therefore be fitted in any convenient position in the receiving cabin.

The two air condensers are mounted on the same spindle so that both aerials can be tuned simultaneously by rotating one handle. It is, however, almost impossible to ensure that they have equal capacity throughout the whole of their common range of movement, and it is therefore usual to provide an independently adjustable billi condenser (B, Fig. 284) in parallel with the one which has the smaller capacity, in order to compensate for the difference.

Fig. 287 shows a goniometer suitable for working over a fairly wide range of wave-lengths. For the lower part of the range the aerials are tuned by the two air condensers C_1 and C_2, which are controlled by the handle H, while the upper part of the range is obtained by inserting in parallel with them two mica condensers C_3 and C_4 by means of the switches S_C. The billi condenser for fine tuning is shown at B; the aerial switches at S_A; the open-wound goniometer coils at G_1 and G_2, and the exploring coil at E.

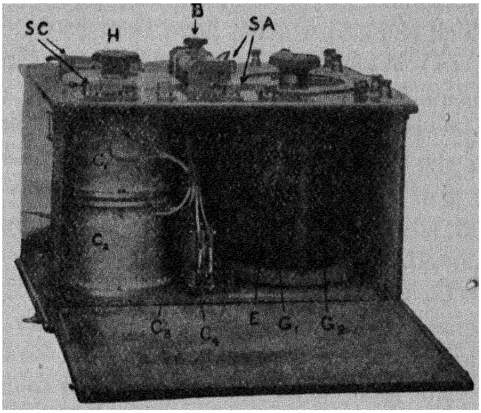


FIG. 287.—View of Ship Type Radiogoniometer.

The Method of Working the Direction Finder.—The usual routine is as follows:

(1) The ship's main aerial is intentionally mis-tuned to the wave-length on which the D.F. is receiving, or alternatively, it is entirely disconnected from earth.

(2) The tuning tester is set to the signal wave-length expected, and its buzzer is switched on.

(3) The following method is then used for bringing the aerials into resonance:

(*a*) One of the switches on the goniometer is opened in order to break the circuit of one aerial, and the variable condenser is adjusted until signals are a maximum—the moving coil handle being preferably set so that the pointer is at 0° or 90° on the scale.

The receiver circuits are also adjusted.

The moving coil is then rotated until signals are weaker, when a finer adjustment can be made.

(*b*) The switch on the goniometer is now closed so that both the aerials are in circuit. They will both be adjusted to the same wave-length except for the slight difference in capacities between the air condensers. To correct for this, set the pointer in the position where signals are at a minimum, and vary the billi condenser until the sound in the telephones of the receiver is reduced to zero.

The adjustment is now exact, the two aerial circuits being in true balance, and the instrument will now indicate the direction of any station sending signals of the wave-length for which the adjustments have been made.

(4) When the wave-length of the signals from the distant station is unknown:

Switch open one aerial and receive from this station on the other; adjust the aerial condensers and the receiver to give maximum signals; then set the tuning tester buzzing and adjust it until the tester signals have also a maximum strength.

Close the second aerial switch, and balance out the tester signals by adjusting the billi condenser as already described; then switch off the tester.

The goniometer can then be used to determine the direction of the distant station.

(5) If the signals are now received, the direction of the transmitting station can be determined by rotating the goniometer handle and noting the scale position of the pointer at which signals in the telephone are loudest. The ear, however, can judge more accurately the difference in intensity of weak signals than of strong signals, so that the following method is to be preferred:

The goniometer handle is turned first to one side of the maximum, then to the other, to find the two points at which signals absolutely disappear. The scale position midway between them will give the direction of the transmitting station.

Again, if the handle is rotated past these points it will find two others, one on either side of the maximum, at which signals reappear.

The position midway between each pair of zero points on either side of the maximum, should give a direction exactly 90° to that of the transmitting station.

The mean reading given by all the zero points should be used.

Thus, if in Fig. 288 the abscissa represents the goniometer scale of 360° spread out straight, with audibility current as ordinate, two maxima, M and N, will be found in one complete rotation of the handle, and four zero positions A, B, C, and D. A, B, C, and D being more sharply defined are first determined, and are then used to find M and N.

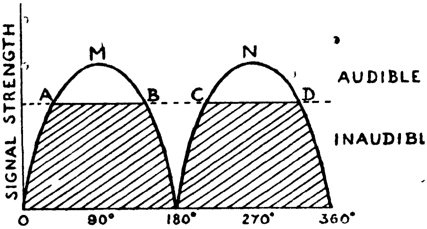


FIG. 288.—Curve illustrating the Angular Range of Audibility of the Goniometer Search Coil.

Causes of Error.—If the signals cannot be reduced to zero, it indicates that the two aerial circuits are electrically unsymmetrical.

One of them may have a greater resistance than the other, caused possibly by leaky insulation on one aerial only, or perhaps by a bad terminal connection.

One aerial may have less inductance than the other, due to its dimensions being wrong, or to it sagging more than the other. The greatest care is taken in winding the goniometer coils to ensure that they have no mutual inductance, and that they are in perfect inductive balance, so that on no account should they be disturbed; error is not likely to be caused, either, by the exploring coil, unless it gets out of centre through damage in transit.

There may be a difference in capacity between the two aerial circuits. The sagging of one of the aerials, the close neighbourhood to one of them of a large metallic object, or any difference in the capacities of the adjustable air condensers which has not been compensated for by the billi condenser, would account for this.

To ensure that the aerials are set up exactly at right angles to each other, note the goniometer scale positions of zero signals for each aerial separately. They should be 90° apart.

Accuracy of observation can only be attained if the apparatus is kept in good working order; the aerials should be kept taut, and frequent inspection is very necessary.

The Distance of the Transmitting Station.—If a ship requires to obtain the exact position of a land-transmitting station, it must take two observations with its D.F. plant, separated by a definite interval of time during which it maintains its course without deviation. Then its speed being known, the distance of the fixed station can be at once determined by laying out a triangle to any convenient scale, having the distance travelled in the given time as base-line, and the two angles of direction as base angles. The intersection of the lines forming these angles with the base will give the position of the fixed station, and its distance can then be measured to scale.

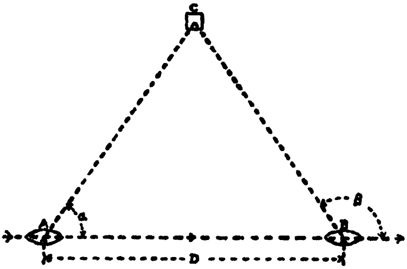


FIG. 289.—Finding the Position of the Transmitting Station by Triangulation.

If tables of sines and cosines are available, the position can be calculated as follows:

Let the first observation taken by the ship at A (Fig. 289) give a D.F. angle with the ship's course of a°. After travelling a known distance D, a second observation taken at B gives a D.F. angle of β°.

Then it can be shown that the distance of the ship at B, from the transmitting station C, is given by the formula

$$CB = D \times \frac{1}{\sin\beta\,(\cot a - \cot\beta)},$$

and the distance when the first observation was taken

$$AC = D \times \frac{1}{\sin a\,(\cot a - \cot\beta)}.$$

Land D.F. stations must work in pairs if distance measurements have to be made.

They can be assumed to take the place of the two ship positions A and B in Fig. 289. Then the distance between them, D, being known and used as a base-line, an observation made at each station of the angle between the direction of the unknown station C and this base-line—the *interior* angle at B being used in this case—will enable the position of C to be plotted out as before; or by calculation—

$$CB = D \times \frac{1}{\sin\beta\,(\cot\alpha + \cot\beta)},$$

and

$$AC = D \times \frac{1}{\sin\alpha\,(\cot\alpha + \cot\beta)}.$$

If the station C is moving—a cruising airship, for instance—the observations at A and B must be made simultaneously.

Direction Finder Land Sets.—On land the size of the aerial is not limited by a short base-line, so that it is possible to obtain better results on long wave-lengths.

In the general case, two triangular aerials are used, which are erected in planes NE – SW and NW – SE.

They are supported at their apexes by a double groove insulator, fixed on the top of a single wooden mast, which may be 70 ft., 90 ft., 120 ft., or 150 ft. in height.

For receiving very long waves, transverse rectangular aerials are used, supported by four masts.

The horizontal bases of the triangles—or rectangles—are 6 ft. above the ground, and are stayed out through insulators to ground anchors, which are so arranged that the two aerials lie in planes which are truly at right angles to each other, and at the same time bisect the angles between the mast guys.

A special form of insulating clamp fixed to the mast holds the base wires taut at the centre, so that the four free ends can be led without strain through the wall insulators of the receiving hut.

There is generally sufficient room available in a land station to allow the apparatus to be well spread out on the receiving bench, as shown in Fig. 290, which is always an advantage where accurate tuning is concerned, and possible reaction effects between the circuits have to be considered.

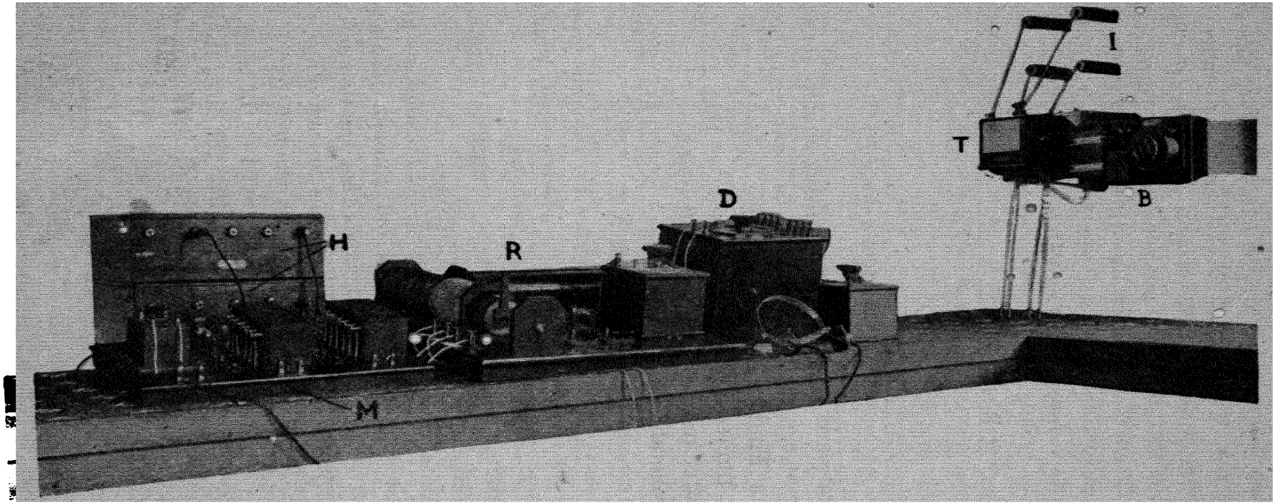


Fig. 290.—The Lay-out of Apparatus in a Land D.F. Station.

The four aerial leads enter at I, and are led down the channels in the tuning buzzer box, T, to the terminals of the radiogoniometer, D. The buzzer box in this case contains only a coupling coil, as shown in Fig. 291, the rest of the circuit, consisting of an adjustable condenser, a buzzer, switch, and dry cells, being mounted on the board B, which is also shown in Fig. 292. The radiogoniometer is made up in a box by itself (Fig. 293); the aerial tuning air condensers are separate and independently adjustable, a large and a small condenser—for coarse and fine adjustment—being provided for one circuit, and a large condenser only for the other.

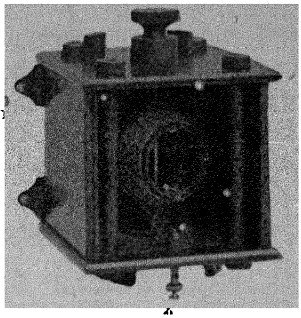


FIG. 291.—The Buzzer Coupling-Coil Box.

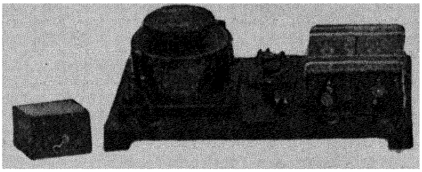


FIG. 292.—The Buzzer Tuning Tester Board.

Various types of receiver are used, a good combination for long wave-lengths being the Marconi type No. 49 (R, Fig. 290), with a double note amplifier, M, and valve high-tension battery, H, which is also shown diagrammatically in Fig. 294.

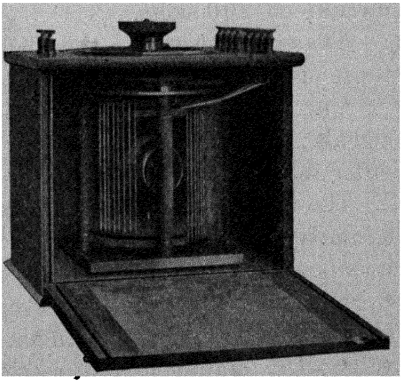


FIG. 293.—The Radiogoniometer of a Land Set.

The jigger primary is connected direct to the goniometer exploring coil, and as the circuit does not include a condenser it is aperiodic in character, and therefore does not require tuning.

The jigger secondary—which can be increased in length by means of a double-pole double-throw switch for the reception of long waves—is tuned by an adjustable air condenser, and is connected to the grids and filaments of two rectifying valves. The common plate circuit includes a reaction coil and the primary of an iron-core telephone transformer on the note-amplifier board. This transformer has a special winding for applying the rectified signal potentials to the grid and filament of the first note-amplifying valve, and—if further amplification is required—a similar transformer is employed to transfer the signals to a second note-amplifying valve, which contains a simple telephone transformer in its plate circuit.

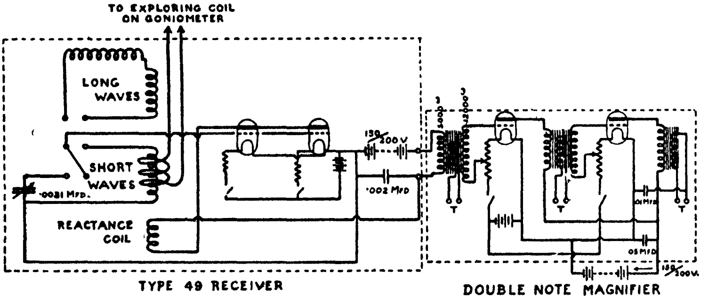


FIG. 294.—A Valve Receiver Circuit employing Note Amplification, used in a D.F. Land Set.

The filaments are run off 6-volt batteries, and the plate circuits off 200 volts.

There is a switch in the filament circuit of each valve, and those circuits which are not in use should be left open.

One valve on the receiver is usually sufficient for spark signals; but when it is necessary to set them oscillating—in order to produce beats in continuous waves—two are better.

The angular position of the reaction coil is important, particularly when receiving C.W. For the longer wave-lengths it is necessary to use a tighter coupling.

Fig. 295 illustrates the bench lay-out of another set. It employs an enclosed tuner, R, and an enclosed seven-valve H.F. amplifier and rectifier, M. This amplifier has already been described in Chapter V.

A D.F. Set with Rotary Frame Aerial.—This type of installation has been developed for portability and quick search on short wave-lengths.

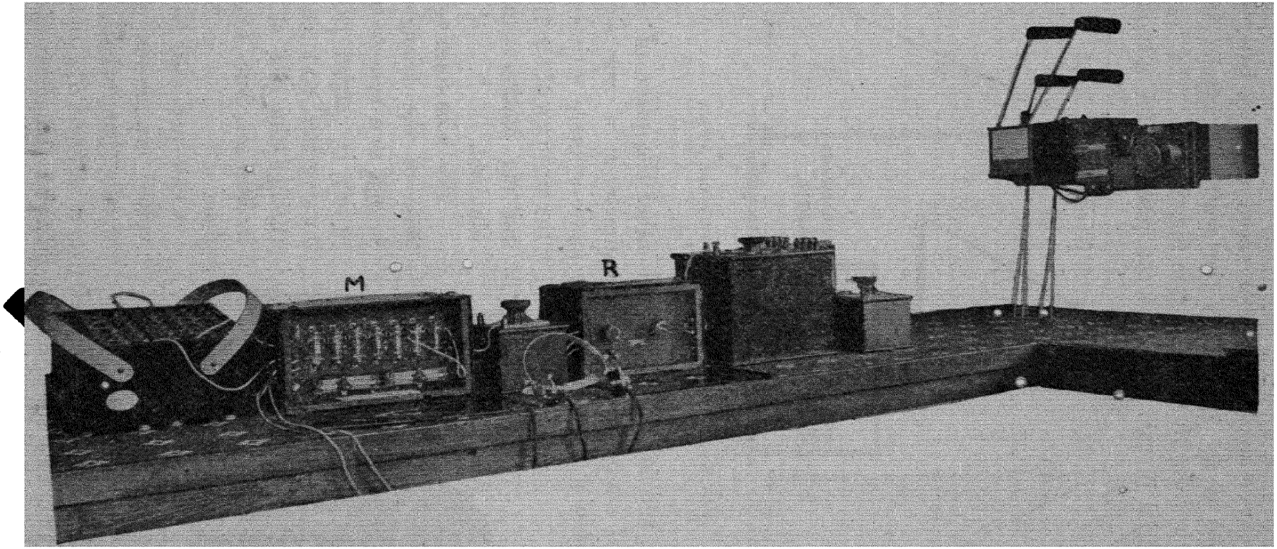


FIG. 295.—The Lay-out of D.F. Land Set which employs H.F. Amplification.

It employs a single triangular aerial of 12 ft. base, which is swivelled at its apex from the centre of a rope triatic supported by two 30 ft. masts (see Fig. 296).

The aerial in this set takes the place of the goniometer search coil, and is rotated to find either the plane of maximum signal strength, or else the directions of zero signals on either side of it from which a more accurate estimate of the direction of the transmitting station can be obtained.

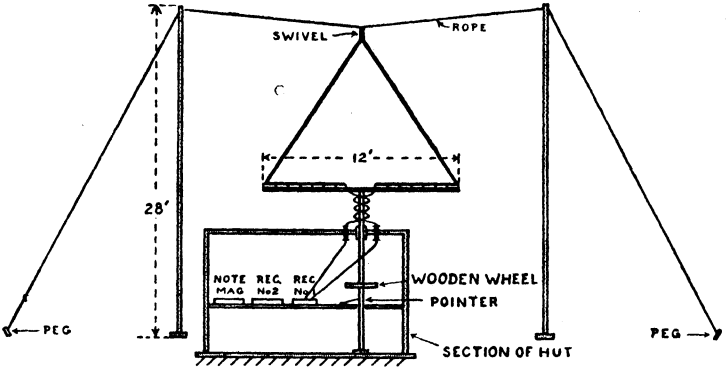


FIG. 296.—A D.F. Set with Rotary Frame Aerial.

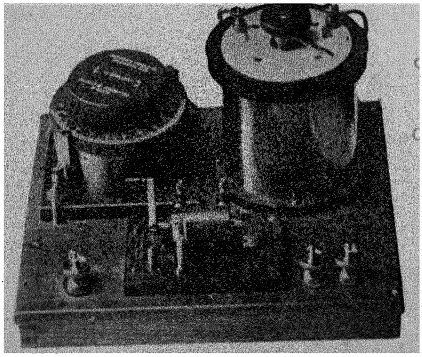


FIG. 297.—Aerial Change-over Board "Std bi" to "Tune" for Quick-search Set.

The wire forming the base of the triangle is lashed to a bamboo pole, which is carried rigidly by a vertical post passing through the roof of the instrument hut to the floor.

This pole can be revolved by means of a wooden hand-wheel, and a horizontal pointer which moves over a scale on the operating bench indicates the direction in which the plane of the aerial is set.

As shown in Fig. 296, connections are taken from the middle of the base of the triangle to the receiver, which is split up into three parts:

(1) A condenser board fitted with a switch to change over

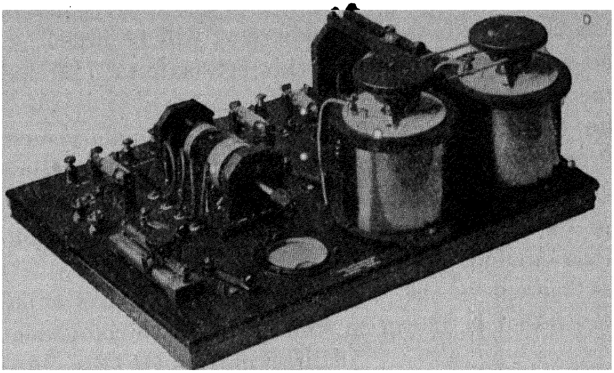


FIG. 298.—H.F. Amplifier and Receiver Board for Quick-search Set.

from "Std bi" to "Tune," a view of which is given in Fig. 297.

(2) A high-frequency amplifier and valve detector board, Fig. 298; and

(3) A note-amplifier board, as illustrated at M, Fig. 290.

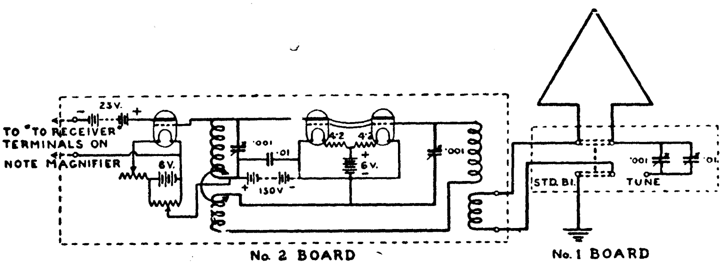


FIG. 299.—The Aerial and Receiver Circuit of the Quick-search Set.

A simplified diagram of the circuit omitting the note amplifier is shown in Fig. 299.

On "Std bi" the two ends of the aerial are connected together and to earth through the coupling coil on board No. 2.

On "Tune" the connection to earth is broken, the two ends of the aerial are separated, and it becomes part of a closed oscillatory circuit, which includes the adjustable air condensers on board No. 1 and the coupling coil on board No. 2.

The provision for the simultaneous adjustment of the two jigger circuits on board No. 2, by means of the band coupling between the adjustable air condensers, will be noted.

The wave-length range of this set is from 120 metres to 700 metres.

The Measurement of Audibility.—Signals are conveyed to the ear by the air displacement caused by the vibration of a telephone diaphragm.

The diaphragm only vibrates when there is variation in the telephone current.

The current in the usual detector circuit has a pulsating character; that is, it can be split up into two components: (1) a direct current OI (Fig. 300); and (2) an alternating current of amplitude II, superposed on OI.

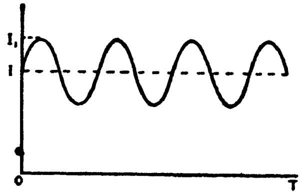


FIG. 300.—The Telephone Current and the Audio Current.

It is this A.C. component which causes the diaphragm to vibrate, and which is called the *audio current.*

Audibility is the ratio of the amplitude of this audio current to the minimum current amplitude of the same frequency and wave-form to give distinct signals.

The determination of this minimum value, which is called the *audibility current* of the particular telephone used, involves a personal factor, as it rests finally on the judgment of the operator, who has to decide at what adjustment he can just distinguish the difference between dots and dashes.

The existence of other noises—atmospheric discharges heard in the telephone, or room or street noises coming from outside the circuit, also the fit of the telephones to the ears, whether tight or loose—unavoidably influence the operator's decision.

Any efficient method, therefore, which could be employed without introducing a personal factor would be much preferred.

The audio current measured is that obtained under the most favourable conditions from the aerial signal current, that is—(1) when the coupling between the aerial and detector circuits is loose enough to prevent any appreciable increase in the damping of the aerial current; and (2) when there is no regenerative action between the two circuits.

A common arrangement is shown in Fig. 301. The aerial couples loosely with a tuned jigger circuit, and a crystal detector is used as a rectifier in series with a telephone T, which is shunted by a variable non-inductance resistance R.

A telephone condenser C, of small H.F. reactance, is used, in order to prevent any change in the radio-frequency current due to alteration of the shunt resistance, as this would react back on the current of audio-frequency.

The shunt resistance is reduced until the signals in the telephone can only just be read.

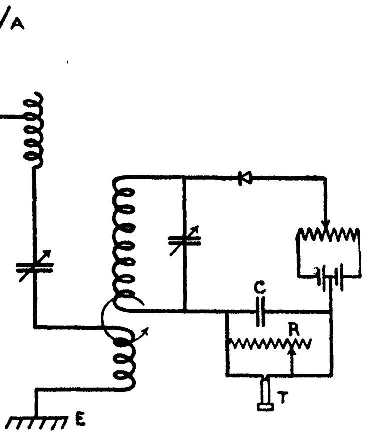


FIG. 301.—Diagram of Circuit used for measuring Audibilities by the Shunted Telephone Method.

Then audibility, A, is the ratio of the current I through the unshunted telephone, to the current I_R through the telephone when shunted by the resistance R, or

$$A = \frac{I}{I_R} = \frac{t + R}{R},$$

where t is the *effective* resistance, or impedance of the telephone under the given conditions of audio frequency and wave-form, or

$$t = \sqrt{R_t^2 + (2\pi n L)^2},$$

the assumption being made that shunting the telephone makes no difference to the audio current.

It is often the practice to neglect the inductance of the telephone and make

$$A = \frac{R_t + R}{R}.$$

This is a mistake unless L is very small compared with R_t. The reactance of telephones used in radio-circuits is frequently of the same order as the resistance.

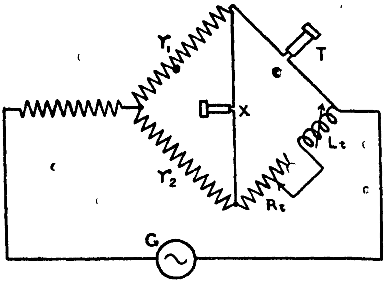


FIG. 302.—An Impedance Bridge Circuit.

The resistance and inductance of the test telephones can be measured by a bridge method such as is used for other inductance tests, the circuit diagram being shown in Fig. 302.

The two non-inductive ratio arms r_1 and r_2 being set to suitable values, the resistance and inductance of the telephone T under test, are balanced for currents at the working audio frequency as delivered from the source G, by adjusting the non-inductance resistance R_t and the inductance L_t until the bridge telephone X is quite silent. This state will be reached when

$$\frac{r_1}{r_2} = \frac{\text{tel. resist.}}{R_t} = \frac{\text{tel. induct.}}{L_t}.$$

It will be found that the telephone resistance and inductive reactance increase with the frequency, except for a sudden fall which occurs when the frequency is in resonance with the natural vibration of the diaphragm; see Fig. 303.

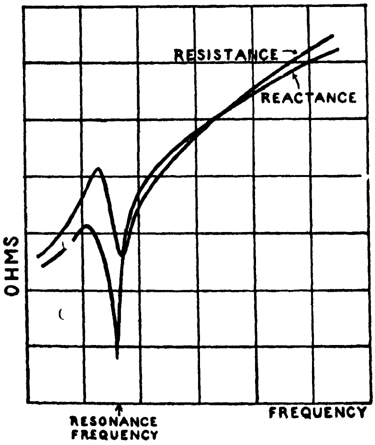


FIG. 303.—The Variation of Telephone Resistance and Reactance with Frequency.

If there are no means available for measuring the impedance of the telephone, absolute audibilities cannot be measured, but if the telephone direct-current resistance is high compared with the shunt resistance, the inverse of the shunt resistance can be used without much error as a measure of comparative audibility.

Take as an example a telephone which has a direct-current resistance of 2000 ohms and an impedance at 500 cycles of 5000 ohms; then suppose the shunt resistances required for two audibility tests were 5 ohms and 50 ohms respectively.

Then the ratio of the absolute audibilities would be

$$\frac{5000+5}{5} \Big/ \frac{5000+5}{50} = 9{\cdot}91 : 1 ;$$

whereas the ratio of the comparative audibilities as given by the shunts alone would be

$$\frac{1}{5} \Big/ \frac{1}{50} = 10 : 1.$$

In such a case, accuracy would be improved by using a high non-inductive resistance in series with the telephones.

Comparative audibilities can also be measured by using a fixed value of resistance R (Fig. 304) in the circuit, and varying the tapping point for the shunted telephone connection. Then if the impedance of the telephone is great compared with that of the resistance, the audio current will not be appreciably affected by any change in shunt adjustment.

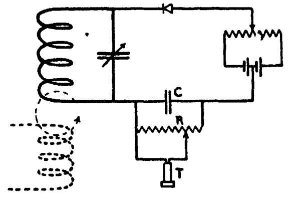


FIG. 304.—Comparative Audibilities by a Potentiometer Method.

The Relation between the Aerial Current received and the Audio Current.—This can best be determined by means of an independent standard circuit used as a generator of local oscillations, which can be adjusted to the frequency of the incoming waves *and to the same decrement.*

Such a circuit is shown in Fig. 305. It consists of an adjustable air condenser C, an inductance coil L having a coupling with the aerial at M which can be varied, and a non-inductive slider resistance R.

The circuit is excited from a battery B, which, by means of either the vibrator of a shunted buzzer SG (*a*), or a commutator (*b*), alternately charges the condenser C and then allows it to discharge through the standard circuit.

The R.M.S. value of the oscillatory current indicated by the ammeter I, depends on the potential applied to the condenser, which is regulated by the slider P.

An adjustment should also be provided for varying the charging or note-frequency.

To make use of the arrangement—

(1) The standard circuit is first adjusted to the same note and wave-length of the signals transmitted by the distant station.

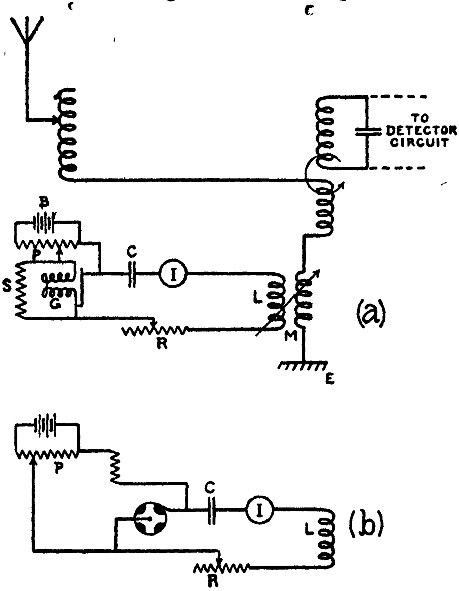


FIG. 305.—An Independent Standard Circuit used for measuring the Relation between the Aerial Current and the Audio Current.

(2) The coupling of the standard circuit with the aerial at M, and its oscillatory current I, are then adjusted to give the same audibility in the receiver as the distant signals.

(3) The aerial is next de-tuned by a small amount, or a small resistance is inserted in it. If the standard circuit has the correct decrement, the two audibilities will still remain equal, although less than before.

If they become unequal, then R must be varied until the correct value is found which makes them equal at both aerial adjustments.

(4) The variable coupling M should now be calibrated, either by calculation or measurement; and the constants of the standard circuit and the aerial circuit being known, the aerial current corresponding to the standard circuit I for any setting of the coupling can then be obtained.

If an aerial ammeter is available, the calibration of the coupling of course becomes very simple.

(5) Finally, the audibilities corresponding to various values of aerial current require to be taken, so that any

audibility within the range measured, produced by signals from the distant station, will be known to correspond to a given aerial current.

When the incoming signals are continuous oscillations, the standard circuit must also be excited by a continuous wave oscillator such as a valve generator. The resistance R will not be required, as no adjustment for decrement will be needed. The provision of a beat-producing circuit will allow any desired note to be obtained.

INDEX

A.C., characteristics of, 22
  generators for valve circuits, 130
  measurement of capacity, 207
    of inductance, 215
Aerial capacity, effective, 167
  circuit damping, 297
  current distribution, 300
    and audio current, 321
  D.F., for ship use, 303
  directional effect, 302
  energy radiated, 300
  inductance, 219
  insulator, flexible type, 273
    "Turnbull" type, 274
  resistance, effective, test of, 298
Air compressor, 151
  core transformer and ammeter, 186
  dielectric strength, 256, 261
  engine, Creed, 152
  gap resistance, 46, 285
Alternating current and potential curves, 26
Alternator, Alexanderson, 74, 76, 77
  Duddell 2000-cycles, 72
  Goldschmidt, 81
  high-frequency, 71
  low-frequency, 53, 71
  S.F.R., 79
  inductance, 216
  maximum output, 33
Ammeter, definition of, 178
  Duddell thermo-, 184
  dynamometer, 180
  hot-wire, Hartmann and Braun, 181
  H.F., Hartmann and Braun, 183
  Marconi-Ewen, 184, 186
  moving-coil, 179
  parallel-wire, 184
  soft-iron, Everett-Edgecumbe, 181
    Weston, 181
Ampere balance, Kelvin, 163
  definition of, 162
Amplification effect, 112, 115
  H.F., 118
  L.F., 118
Amplification of weak signals, 116
Amplifier, H.F., and D.F. set, 317
  type No. 55, 138
    and multiple tuner, 140
  Note, and crystal detector, 142
    and magnetic detector, 141
    and D.F. set, 314
Anderson inductance bridge, 211
Anderson-Fleming bridge, 212
Anode plate of valve, 109
Apparatus, finished, pressure test, 261
Arc characteristics in air, 97, 99
    in hydrogen, 99
  Duddell, 96
    characteristics, 98
    current, 98
  Marconi-Poulsen, 104
  Poulsen, 99
    characteristic, 101
    current and potential, 100
  transmitter, 96
Astatic galvanometer, 167
  system, 167
Atom, the, 4
  and secondary electrons, 8
  electron vortex, 6
  J. J. Thomson, 5
  E. Rutherford, 6
  N. Bohr, 6
  G. W. Nicholson, 6
Atomic core, 5, 6, 7
Atoms, interchanging electrons, 108
  sizes of, 15
Audibilities, comparative, 321
Audibility, 318
  current, 318
  measurement, 318
  range of goniometer, 309
Audio current, 318

Balance, Kelvin ampere, 163
Ballastic galvanometer, 166, 198, 283
Beat frequency, 127
  generator, self-, 128
"Beats," 126

Bellini-Tosi direction finder, Marconi-, 302
Bjerknes decrement test, 290
Blower, motor, 153
Bohr atom, 6
Bridge, Anderson, 211
  Anderson Fleming, 212
  capacity, 204
  impedance, 320
  inductance, slide-wire, 213
  plug, 190
  Post-Office, 191
  resistance, slide-wire, 190
  Wheatstone, 189
Bridges, dial and bar pattern, 191
Burning of spark electrodes, 56
Bushings, insulating, 276
Buzzer circuit, calibrating, 245

Cadmium cell, 172
Calibrating buzzer circuit, 245
  of galvanometer, 174
  of voltmeter, 175
  of disc discharger, 59
  of wave-meter, 243, 245
  of condenser tubes, 205
Campbell mutual inductance, 220
  speed constancy indicator, 238
Campbell-Paul spark counter, 237
Capacity bridge, 204
  measurement of, 200
  by A.C. measurement of, 207
  by direct charge, measurement of, 201
  by H.F. resonance, measurement of, 208
  of an aerial, 209
  inductance and resistance in circuit, 32
  commutator, Fleming-Clinton, 202
Cell, standard, 172
Characteristic of an arc, dynamic, 97
    static, 97
  falling, 96
  two-electrode valve, plate, 110
  grid-plate, 114
Characteristics of Duddell arc, 98
  of working Poulsen arc, 101
Charge, space, 113
Chemical action, 14
Compressor, air, 151
Condenser, charge and discharge of a, 27, 29, 30
  discharge circuit, 45
  for smoothing wave-form, 125
  plate, "Rendahl," 268
  tubes, calibration of, 205
Condensers, pressure testing of, 266
Conductivity of spark gap, 48
Conductor, electrical state of glowing, 108
Continuous wave transmitters, 70
  oscillations by "Timed Spark," 91
Continuous oscillations by valve, 123
"Control" valve, 149
Core, atomic, 5, 6, 7
Corrugation and insulation, 278
Coupled circuit decrements, 286
    oscillations, 64, 65, 289
  circuits, 220
Coupling, coefficient of, 221
  capacity, 121
  degree of, 287
  percentage, 287
  waves, 246, 247
Creed air engine, diagram of, 150
  description of, 152
  relay, 152
Critically damped movement, 166
Crystal detector and amplifier, 142
Cumulative rectification, 122
Current, nature of alternating, 22
    of direct, 21
  average, 179
  dead-beat, 29
  grid, 114
  plate, 114
  root-mean-square, 180
  measurement of, 162
  amplification by resonance, 45
  indicating instruments, 177
  distribution in aerial, 300

Damped oscillations in coupled circuits, 289
Damping, 281
  in aerial circuit, 297
  of galvanometers, 166
  of pendulum, 280
D'Arsonval galvanometer, 165
Dead-beat current, 29
  movement, 166
Decay factor, 282
Decrement, measurement of, 280
  definition of, 281
  logarithmic, 281
  lineal, 285
  spark, 285
  non-sparking circuit, 284
  radiation, 299, 300
  earth-system, 299
Decrements of coupled circuits, 286
  with spark, 288
  without spark, 287
  measurement by tuning curve, 289
  by Bjerknes method, 290
Decremeters, Marconi, 292, 295, 296
Degree of coupling, 287
Detector, crystal, with amplifier, 118, 134, 142
De-tuning a quenched spark circuit, 68
D.F. system, Marconi-Bellini-Tosi, 302

D.F. aerial for ship use, 303
  set for ship use, 304
  receiver for ship use, 305
  tuning tester for ship use, 305
  working theory, 306
  method of use, 307
  causes of error, 309
  land sets, 311
    apparatus for, 313
  receiver and note amplifier, 314
  rotary and frame aerial, 314
Dial pattern bridge, 191
Diamagnetic effect, 10
Dictaphone reception, 157
  spark record, 234
  cylinder shaving machine, 159
Dielectric hysteresis, 251
  strengths, table of, 261
  strength, measurement of, 248
    wave-form and, 249
    units, 251
Dielectric strength test of varnish, 252
  of mica, 253
  of ebonite, 254
  of glass, 255
  of tubes, 259
  of oil, 260
  of raw materials, 251
  on H.T. and H.F., 270
  power required for, 272, 273
Digby oil tester, 260
Direct current, nature of, 21
Directional effect of aerials, 302
Disc discharger, Marconi, 53, 58
    scale for, 55
    calibration of, 59
  electrodes, side, 58
    burning of, 56,
Discharge of a condenser, 27, 29, 30, 45
  quenched spark, 63
Discharger, plain, 62
Disruptive strength, 249
Distance of transmitting station, 310
Dolezalek electrometer, 177
Double frequency changer, 89
  note amplifier, 314
Drysdale-Tinsley galvanometer, 170
  roller stroboscope, 225
Ducter potential ohmmeter, 194
Duddell alternator, 2000 cycles, 72
  arc, 96
  oscillograph, 169, 230
  thermo-ammeter, 184
  thermo-galvanometer, 168
Dynamic arc characteristics, 97, 98, 101
Dynamometer ammeter, 180
  principle, 180

Earth decrement, 299
Earth, resistance, effective, 299
Ebonite, dielectric strength test of, 254
Effective capacity of an aerial, 209
  inductance of an aerial, 219
  resistance of an aerial, 298
Efficiency of an aerial, 299
Einthoven galvanometer recorder, 159
    optical system, 160
  string galvanometer, 171
Electric current, nature of, 3
  measurement of, 162
Electricity, nature of, 1
Electro-chemical dissociation, 15
Electrode rocker, spark, 53
Electromagnetic radiation, 31
  waves, velocity of, 241
Electrometer, Dolezalek, 177
  quadrant, 176
  resistance measurement by, 199
Electron, 2
  field of an, 2
  vortex atom, 6
Electrostatic field of a condenser, 27
    field between various electrodes, 258
  voltmeter, 186
  unit, the, 200
E.M.F., unit of, 172
  measurement of, 172
  due to capacity, back, 27
  due to induction, 20
  measured by potentiometer, 172
Energy radiated from aerial, 300
Ether, 18
Everett Edgecumbe soft-iron ammeter, 181
  frequency meter, 227
Ewen thermo-ammeter, Marconi, 184
Expansion chamber, Marconi arc, 103
Exponential curve, 281

Factor of merit, 165
Falling characteristic, 96
Farad, the, 200
Ferro-magnetic effect, 10
Filament current of three-electrode valve, 116
    and plate characteristics, 111
  of two-electrode valve, 109
Fleming photographic spark counter, 235
Fleming-Anderson inductance bridge, 212
Fleming - Clinton capacity commutator, 202
  inductance commutator, 213
Flexible strain insulator, 273
  semi-, 275
Forest, Lee De, three-electrode valve, 112
Frahms speed indicator, 224
Frequency changers, static, 87
  measurement of, 223

Frequency meter, Everett-Edgecumbe, 227
  Hartmann and Braun, 226
  induction, 227
  Westinghouse, 228
  Weston, 228
  doubling the range of a, 227

Galvanometer, calibration of, 174
  ballistic, 166, 201, 283
  D'Arsonval, 165
  damping of, 166
  definition of, 164
  Duddell thermo-, 168
    oscillograph, 168
  Einthoven, 170
  sensitivity, 164
  single pivot, 192
  Thomson astatic, 167
  vibration, 170
Gaseous emission from hot bodies, 107
Gauge, spark, 258
Generator, H.T., for valve plate circuit, 125
  self-beat, 128
  A.C., for valve circuits, 130
Generators, pressure test of, 263
Geometrical progression, 281
Glass condenser tubes, calibration of, 205
  plates, dielectric strength test of, 255
Glowing conductor, electrical state of, 106
Goldschmidt H.F. alternator, 81
Goniometer, 303
  audibility range, 309
Grid, the, 113
  plate characteristics, 115, 117, 137
  potentiometer, use of, 113
Guard plate in megger, 197
  wire, 164
Guards, for insulators, 278
Guy insulators, 275

Hartmann-Braun hot-wire ammeter, 181
  H.F. ammeter, 183
  frequency meter, 226
Helium, radio-active production of, 13
Henry, the, 211
H.F. amplifier, No. 55, 138
  and D.F. set, 317
High-frequency alternators, 71, 74, 79, 81
High-frequency, pressure testing at, 264, 272
High-speed transmitting apparatus, 150
  receiving apparatus, 157, 159
High-tension signalling switch, 152
Hot-strip ammeter, H. and B., 183
Hydrogen arc, 99
Hysteresis, dielectric, 251

Impedance bridge circuit, 320
Inductance, alternator, 216
  transformer, 215
  Campbell variable mutual, 220
  mutual, 219
  and capacity, circuit containing, 29, 32
  and resistance, circuit containing, 26
  only, circuit containing, 26
  commutator, Fleming-Clinton, 213
  of an aerial, effective, 219
  of transmitting circuit, minimum, 50
  by Anderson bridge, measurement of, 211
  by slide-wire bridge, measurement of, 213
  by drop in potential, measurement of, 214
  by L.F. resonance, measurement of, 216
  by H.F. resonance, measurement of, 218
Induction, 20
  frequency-meters, 227
In-phase current, 32
Instruments, valve, 133
Insulating bushings, 276
Insulation and corrugation, 278
  resistance, 196
  surface, 250
  test by "loss of charge," 198
    by power required for H.T., 272, 273
Insulators, guards for, 278
  "Semi-flexible," guy, 275
  "Walnut," guy, 275
  test of aerial, 273
  "Turnbull" aerial, 274
Intensity of received signals, 309, 318
Ion, 2, 11, 12
Iron in a solenoid, 24

J. J. Thomson atom, 5
Joly and Vallauri double-frequency changer, 89
Joly triple-frequency changer, 90

Kelvin ampere balance, 163
  ether vortex atom, 7

Lagging current, 26
  in alternator, 33
  and spark-discharger, 51
Land sets, D.F., 311
Leading current, 26
Leakage, magnetic, 43
Lecher wire circuits, 241
Lee De Forrest three-electrode valve, 112
Light, velocity of, 240
Limiting power of an alternator, 34
Lineal decrement, 285

Linkage with a conductor, magnetic,
  in a solenoid magnetic, 23
  in coupled circuits, magnetic, 219
Logarithmic decrement, 281
"Loss of charge" method, 198
Low-frequency alternators, 71
  amplification, 118

Magnetic field, ether shear and, 18
  detector and note amplifier, 141
  leakage, 43
Magnetisation by D.C. and A.C., 88
  of iron, 25
Marconi disc discharger, 45, 53
Marconi-Ewen ammeter, 185
Marconi-Mackie disc discharger, 57
Marconi-Poulsen arc transmitter, 103, 104
Mass of the atom, 5, 6
Megger, 197
Merit, factor of, 165
Metallic vapour in spark gap, 49
Microphone in aerial, 129
  in grid circuit, 129
Milli-voltmeter, 178
Mirror speed, accurate measurement of, 238
Model of magnetic field, 18
Models of the atom, 5, 6
Molecule, 15
Motor blower, 153
  Wheatstone, 153, 155
Moving coil ammeter, 179
  principle, 179
Multiple tuner with No. 55 amplifier, 140
Mutual inductance, 219
  Campbell standard, 220

Natural period of a circuit, 30
Needle point voltages, 256
Negative electricity, 2
  ion, 2
Note amplifier circuits, 118, 136, 141, 142, 314
Note amplifier and crystal detector, 142
  and D.F. set, 314
  and magnetic detector, 141

Ohm, the, 188
Ohmmeter, the, 194
Oil dielectrics, 260
Oscillation frequency, measurement of, 236
Oscillator, valve, 124
Oscillatory current defined, 29
  production of an, 44
Oscillatory valve phenomena, 123
Oscillograms of sparking circuit, 52
Oscillograph, Duddell, 168
Oscillograph, frequency measurements by, 230
Oscilloscope, Gehreke, 230

Parallel wire ammeter, 184
Paramagnetic effect, 10
Pendulum, damping of a, 280
Percentage coupling, 287
Perforator, Wheatstone, 155
Phase displacement effects, 17
  and spark discharge, 44
Photographic recorder, Marconi-Einthoven, 161
Photographic spark counter, Campbell-Paul, 237
  Fleming, 235
Plain spark discharge, 62
Plate anode of valve, 109
  characteristic of two-electrode valve, 110
  potentiometer and two-electrode valve, 112
Porcelain insulators, 275
Positive electricity, 2
  ion, 3
Potential, resistance measurement by fall of, 193
  indicating instruments, 177
Potentiometer, E.M.F. measurement by, 172
Poulsen arc, distinctive features, 99
  working characteristic, 101
  current and potential, 100
  diagram, 102
  Marconi, 103, 104
Pressure test, duration of, 261
  H.F., 264, 272
  of condensers, 266
  of generators and motors, 263
  of transformers, 264
  of windings, 264
Punched slip, 154

Quadrant electrometer, 176
  discharge, 63
Quenched spark and de-tuned circuits, 68
Quenched spark discharger, Marconi type, 67
  Telefunken type, 66
Quick-search D.F. set, 314

Radiation decrement, 299, 300
Radiation, electromagnetic, 31
Radio-active effects, origin of, 12
Radiogoniometer, 303
  ship type, 305
    view of, 307
  land type, view of, 313
Reaction coil, use of a, 120
Receiver type, No. 27, 133

Receiver type, No. 38 (*a*), 135
Reception by dictaphone, 157
Recording dictaphone, 158
Rectification effect, 108, 115
  cumulative, 122
  efficiency of, 119
  simple, 122
Reed type frequency meter, 226
Relay, Creed, 152
Reluctance, 25
"Rendahl" condenser plate, 268
Residual charge, 207
Resistance, aerial effective, 298
  earth system effective, 299
  spark-gap, 49, 285
  insulation, 196
  measurement by galvanometer, 188
  capacity and inductance in a circuit, 195
  standards, 188
Resonance, 32
  current and P.D. amplification by, 45
  in circuit when sparking, 50
  and spark discharge, 49
  wave-length and tuning curve, 291
Retro-active effect, 120
Rocker, 53
Root-mean-square current, 180
Rotary frame aerial, 314
Rotary disc discharger, 53
  C.W., 91
Rutherford atom, 6

Saturation current, 110
Secondary electrons, 8
  effect of heat on, 107
Semi-flexible guy insulator, 275
Shaving machine, dictaphone cylinder, 159
Shear in the ether, 18
Ship D.F. set, 304
Signalling switch H.T., 152
Single pivot galvanometer, 192
Sizes of electron vortex atoms, comparative, 16
Slide-wire resistance bridge, 190
  inductance bridge, 213
Slip, punched, 154
"Soakage," 207
Soft-iron ammeters, 180
Solenoid, magnetic field in a, 23, 24
  iron in a, 24
Space charge, 113
Spark counter, Fleming photographic, 235
  Campbell-Paul photographic, 237
Spark discharge, the, 44
  discharge at zero charging current, 46
  electrodes, the burning of, 56
  electrode rocker, 53
Spark frequencies, table of, 240
    measurement of, 233
    tape record, 234
  decrement, 285
  resistance, 285
  gauge, 258
  record by dictaphone, 234
  phase, calibration of discharger for, 59
    adjustment, 60
    scale of, 55
  "make" and "break," 56
Sparking period in each A.C. half cycle, 92
  voltages, 256
Specific inductance capacity, 200
Speed constancy indicator, Campbell, 238
  measurements, 223
Standard cell, 172
  resistances, 188
Stark, valency electrons of, 6
Static characteristic of an arc, 97
Stationary waves along wires, 241
String galvanometer, Einthoven, 170
Stroboscope, Drysdale roller, 225
  controlled by tuning fork, 238
Stroboscopic methods, 224
Strongly damped oscillations, 65
Surface insulation, 250

Table of spark voltages, 256, 257
  of spark frequencies, 240
  of dielectric strengths, 261
  of specific inductive capacities, 201
Tape record of spark frequencies, 234
Telephone, calibration of disc discharger by, 59
  impedance, 319
  resonance, 320
  transmitter, valve, 128
    and receiver, short distance, 142
    and receiver, type T.T. 2, 145
    and receiver, type T.T. 3, 148
Temperature and electron emission, 107
Tester, tuning, 245
  D.F. tuning, 305
Thermo-ammeter, Duddell, 184
  Marconi-Ewen, 185
  Hartmann and Braun, 181
Thermo-electric power, 168
  -electric effect, 167
  galvanometer, Duddell, 168
  ionic effects, 106
Thomson astatic galvanometer, 167
Three-electrode valve, 112
Three-electrode valve, types of, 131
Throw of ballistic galvanometer, 283
Ticker, 126
Time of condenser discharge, 45
"Timed Spark" method, 91
Transcribing dictaphone, 158

Transformation ratio, 34
Transformer inductance, 215
  leakage, 43
  H.F. ammeter, 186
  pressure test of, 264
Translational motion of an atom, 11
Transmitter, Wheatstone, 153
  motor control, 155
Transmitters, C.W., 70
Transmitting apparatus, high-speed, 150
  set, 60-kw. spark, 62
Trigger spark circuit, 95
Triple-frequency changer, Joly, 90
Tube dielectrics, 259
Tuning curve and decrement, 289
    and resonance wave-length, 291
  tester, 245
  fork and shutter, 226
    controlling stroboscope, 238
Turnbull strain insulator, 274
Two-electrode valve, 109

Uni-pivot galvanometer, Paul, 192

Valency electrons, 6
Vallauri and Joly frequency changer, 89
Valve, "control," 149
  filament of, 109
  filament current of, 116
  instruments, 133
  oscillator, 105, 124
  plate anode of, 109
  telephone transmitter, 128
  two-electrode, 109
  three-electrode, 112
    types, 131
Vapour in spark gap, metallic, 49
Varnish, dielectric strength test of, 252
Vector quantities, 37
  diagrams of L., C., and R., 38
Vector diagrams of transformer on "No-load," 40
  on "Non-inductive load," 41
  on "Capacity load," 42
Vibration galvanometer, Drysdale-Tinsley, 170
  Duddell, 170
Volt balance, Kelvin, 187
Voltages, spark, 256
Voltmeter calibration, 175
  definition of, 178
  electrostatic, 186
  milli-, 178
Vortex atom, electron, 6
  ratios, 16

"Walnut" insulator, 275
Wave-form curves, compound, 232
  and dielectric strength, 249
  of induction coil, 250
Wave-length measurement, 240, 241, 247
Wave-meter, 241, 245
  calibration of, 243, 245
    by spark frequency, 244
Waves along wires, 241
Westinghouse frequency meter, 228
Weston cadmium cell, 172
  frequency meter, 228
  soft-iron ammeter, 181
Wheatstone bridge, 189
  perforator, 155
  transmitter, 153
Windage on the spark, 57
Windings, pressure test of, 264

X-rays, origin of, 12

THE END

Printed by R. & R. Clark, Limited, *Edinburgh.*

PUBLICATIONS OF

THE WIRELESS PRESS, LTD.

12 AND 13 HENRIETTA STREET,
STRAND, LONDON, W.C.2.

The Year Book of Wireless Telegraphy and Telephony.

British, Colonial and Foreign "Wireless" Laws and Regulations. Price 10s. 6d. net. (Post free, 11s. Inland; 11s. 4d. Abroad.)

The Wireless Telegraphists' Pocket Book of Notes, Formulæ and Calculations.

By Dr. J. A. Fleming, M.A., D.Sc., F.R.S., M.Inst.E.E., etc. A valuable compendium for Wireless Engineers and Operators. Price 9s. net. (Postage 5d.)

The Handbook of Technical Instruction for Wireless Telegraphists.

By J. C. Hawkhead and H. M. Dowsett, M.I.E.E. Provides a complete theoretical course for the Postmaster-General's certificate of proficiency. 310 pages. 240 Diagrams and Illustrations. Price 7s. net. (Postage 6d.)

Manual de Instruccion Técnica para Operadores de Telegrafia sin Hilos.

Por J. C. Hawkhead y H. M. Dowsett, M.I.E.E. Precio: España, 10 pesetas; Franqueo, 1 peseta extra. América Latina, $2.25, oro, neto; Franqueo, 25 cents extra. (Great Britain, 9s.; Postage 6d.)

The Elementary Principles of Wireless Telegraphy.

By R.D. Bangay. In two Parts. Price 3s. 6d. each. (Postage 4d.) Or in one Volume, price 7s. net. (Postage 6d.) Used by H.M. Government for instructional purposes.

Principios Elementales de Telegrafia sin Hilos.

Por R. D. Bangay. (Partes 1a y 2a en un Volumen.) Precio: España, 10 pesetas; Franqueo, 1 peseta extra. América Latina, $2.25, oro, neto; Franqueo, 25 cents extra. (Great Britain, 9s.; Postage 6d.)

PUBLICATIONS OF THE WIRELESS PRESS, Ltd. *(continued)*

Principes Élémentaires de Télégraphie sans Fil.

Par R. D. Bangay. (Great Britain, **9s.** ; **Postage 6d.**)

The Wireless Transmission of Photographs. (Second Edition.)

By Marcus J. Martin. Price **5s.** net. (**Postage 4d.**)

Magnetism and Electricity for Home Study.

By H. E. Penrose. Crown 8vo. Over 500 pages. Price **5s.** net. (**Postage 6d.**) Contains fifty complete lessons.

The Calculation and Measurement of Inductance and Capacity.

By W. H. Nottage, B.Sc. Invaluable to all engaged in Telegraph Engineering. Indispensable to the Wireless Engineer, Student and Experimenter. Price **3s. 6d.** net. (**Postage 5d.**)

A Short Course in Elementary Mathematics and their application to Wireless Telegraphy.

By S. J. Willis. To Students in Wireless Telegraphy, as well as those engaged in the practical application of this Science, this book should prove of real value. Price **3s. 6d.** net. (**Postage 6d.**)

The Marconi Official Gramophone Records.

For self-tuition in receiving Morse Signals. Price **4s.** each, double-sided. (**Postage 9d.**) Set of Six Records, **24s.** post free.

The Maintenance of Wireless Telegraph Apparatus.

By P. W. Harris. An up-to-date Manual, full of practical hints and explanations. Diagrams of all ship installations, from ¼ kw. to 5 kw. Price **2s. 6d.** net. (**Postage 4d.**)

Dictionary of Technical Terms used in Wireless Telegraphy.

By Harold Ward. Vest Pocket Edition. 2nd Edition, revised and enlarged. Contains over 1500 definitions. Price **2s. 6d.** net. (**Postage 2d.**)

Test Questions on Wireless Telegraphy. Invaluable for self-examination.

Series 1. THE ELEMENTARY PRINCIPLES OF WIRELESS TELEGRAPHY. Part I.

Series 2. COVERING THE GROUND FOR THE POSTMASTER-GENERAL'S EXAMINATION.

Series 3. THE ELEMENTARY PRINCIPLES OF WIRELESS TELEGRAPHY. Part II.

Price of each Series of Questions, **2s.** net. **(Postage 3d.)**

MODEL ANSWERS TO THE ABOVE.

Price of each Series of Answers, **2s.** net. **(Postage 3d.)**

Armature Model for 1½ kw. Rotary Converter.

Shows every Winding of the Converter Armature from start to finish. Price **1s.** net. **(Postage 3d.)**

Morse Made Easy.

By A. L. Rye. Linen backed, for rapidly learning the Morse Code. Price **3d.** net, or post free **3½d.**

Morse Code Card.

Contains full alphabet, with punctuation marks, figures, abbreviations and contractions. Price **2d.**, post free.

Practical Wireless Telegraphy.

By E. E. Bucher. 352 pages. 340 Illustrations. Price **12s. 6d.** **(Postage 6d.)**

Radio-Telephony.

By Alfred N. Goldsmith, Ph.D. 256 pages. 226 Illustrations. Price **15s.** net. **(Postage 6d.)**

Standard Tables and Equations in Radio-Telegraphy.

By Bertram Hoyle, M.Sc.Tech., A.M.I.E.E. 159 pages. Price **9s.** net. **(Postage 6d.)**

Vacuum Tubes in Wireless Communication.

By E. E. Bucher. Deals with the Oscillation Valve. 178 pages. 130 Illustrations. Price **12s. 6d.** net. **(Postage 6d.)**

PUBLICATIONS OF THE WIRELESS PRESS, Ltd. (*continued*)

Useful Notes on Wireless Telegraphy. (Students' Library.)
By Harold E. Penrose. Price 1s. 4d. net each. (Postage 2d.)
Book I. DIRECT CURRENT.
Book II. ALTERNATING CURRENT.
Book III. HIGH-FREQUENCY CURRENT AND WAVE PRODUCTION.
Book IV. THE 1½ KW. SKIP SET.
Book V. THE OSCILLATION VALVE.

The Oscillation Valve: The Elementary Principles of its Application to Wireless Telegraphy.
By R. D. Bangay. 215 pages. Price 5s. (Postage 5d.)

The Thermionic Valve and its Developments in Radio-Telegraphy and Telephony.
By Dr. J. A. Fleming, M.A., D.Sc., F.R.S., M.Inst.E.E., etc. 279 pages. Price 15s. (Postage 6d.)

Telephony without Wires.
By Philip R. Coursey, B.Sc., A.M.I.E.E., F.P.S.L. 414 pages. Price 15s. (Postage 6d.)

Alternating Current Work: An Outline for Students of Wireless Telegraphy.
By A. Shore. 163 pages. Price 3s. 6d. (Postage 4d.)

Selected Studies in Elementary Physics: A Handbook for the Wireless Student and Amateur.
By E. Blake, A.M.I.E.E. 176 pages.

The Wireless World.
A Monthly Magazine devoted to Wireless Telegraphy and Telephony. Price 9d. (Postage 3d.) Annual Subscription, 11s. post free.

The Radio Review.
A Monthly Record of Scientific Progress in Radio-telegraphy and Telephony. Price 2s. 6d. (Postage 3d.) Annual Subscription, 30s. post free.

Conquest.
A Popular Illustrated Monthly Magazine dealing with Science, Industry and Invention. Price 1s. (Postage 3d.) Annual Subscription, 15s. post free.

Continuous Wave Wireless Telegraphy. Part I.
By Dr. W. H. Eccles, D.Sc., A.R.C.S., M.I.E.E. [*In the Press.*

COMPLETE CATALOGUE POST FREE.